The Really Big Picture

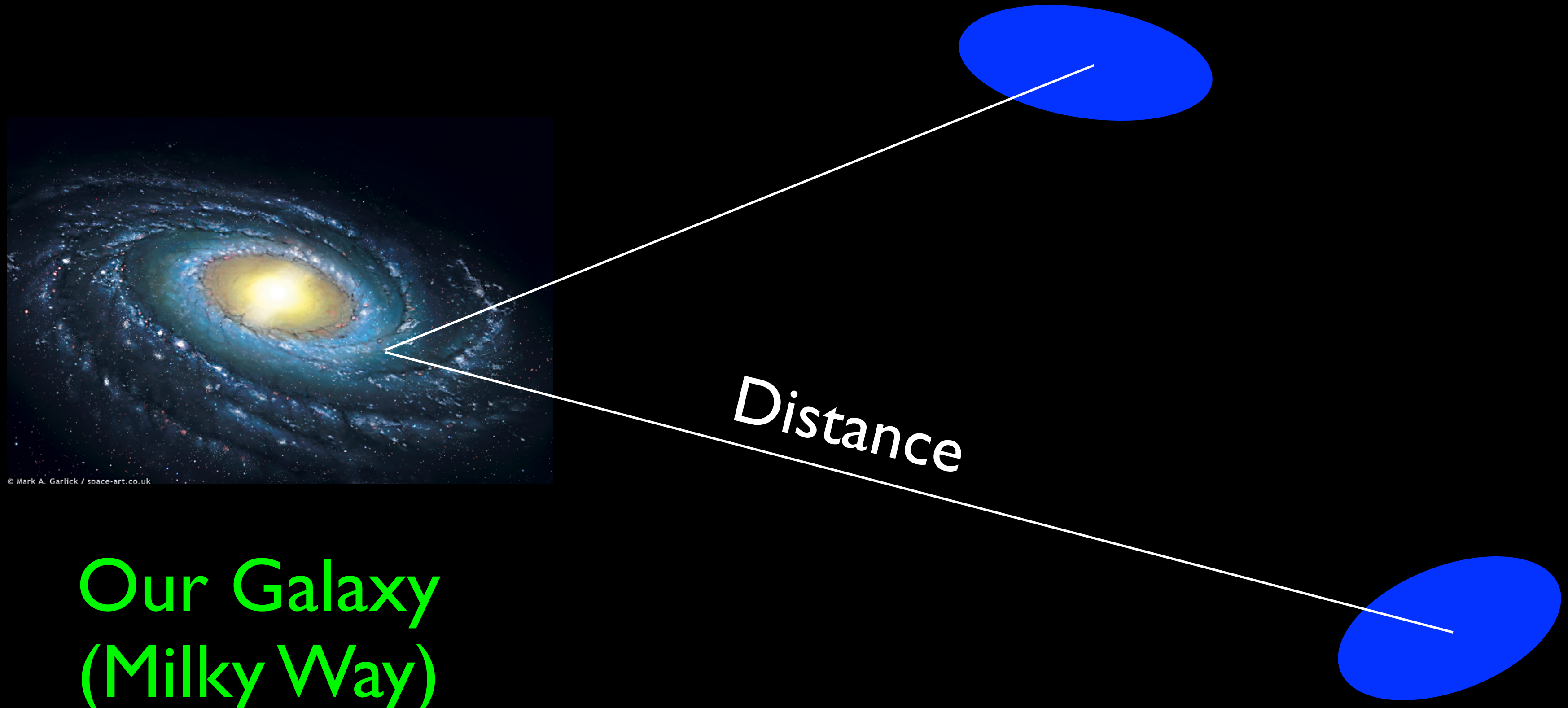
Cosmology in the 21st Century

Paul Stankus
Brookhaven National Lab

The Expanding Universe

Part 1

Distant Galaxies Now



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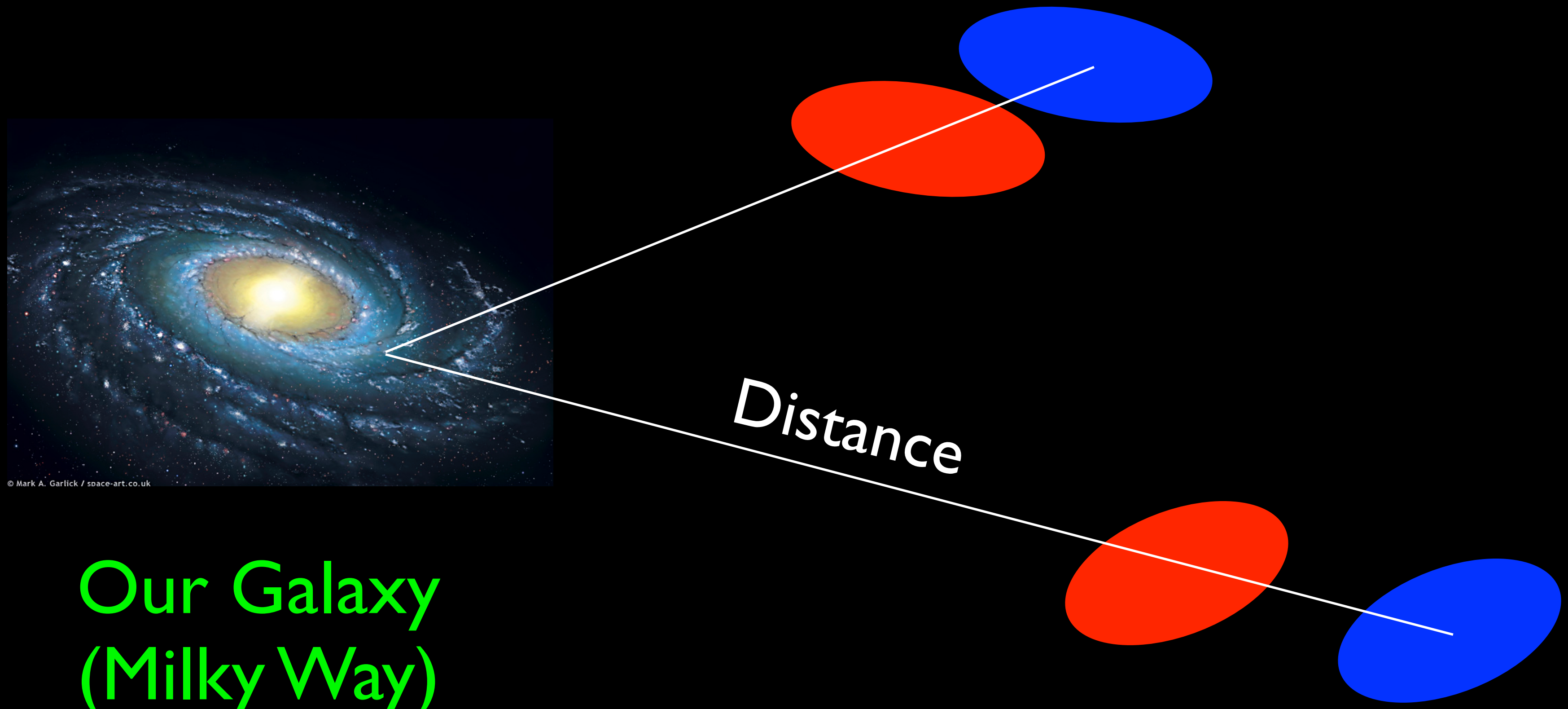
Distance

Our Galaxy (Milky Way)



Distant Galaxies

Earlier

Now

Distance

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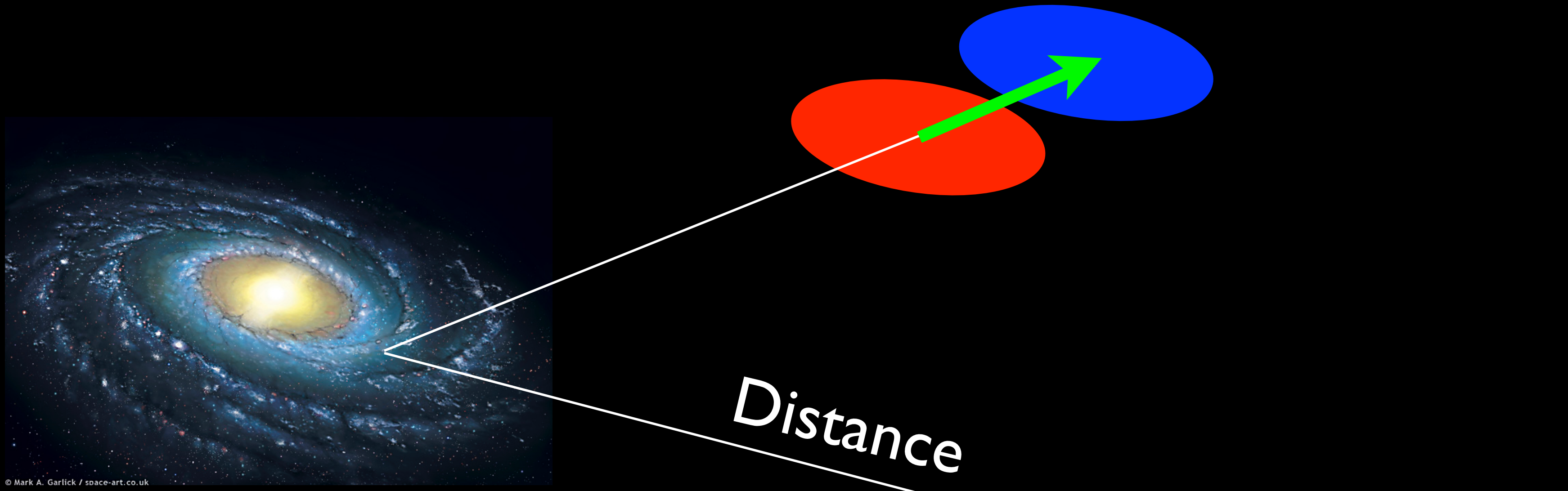
Our Galaxy
(Milky Way)

Distant Galaxies

Earlier

Now



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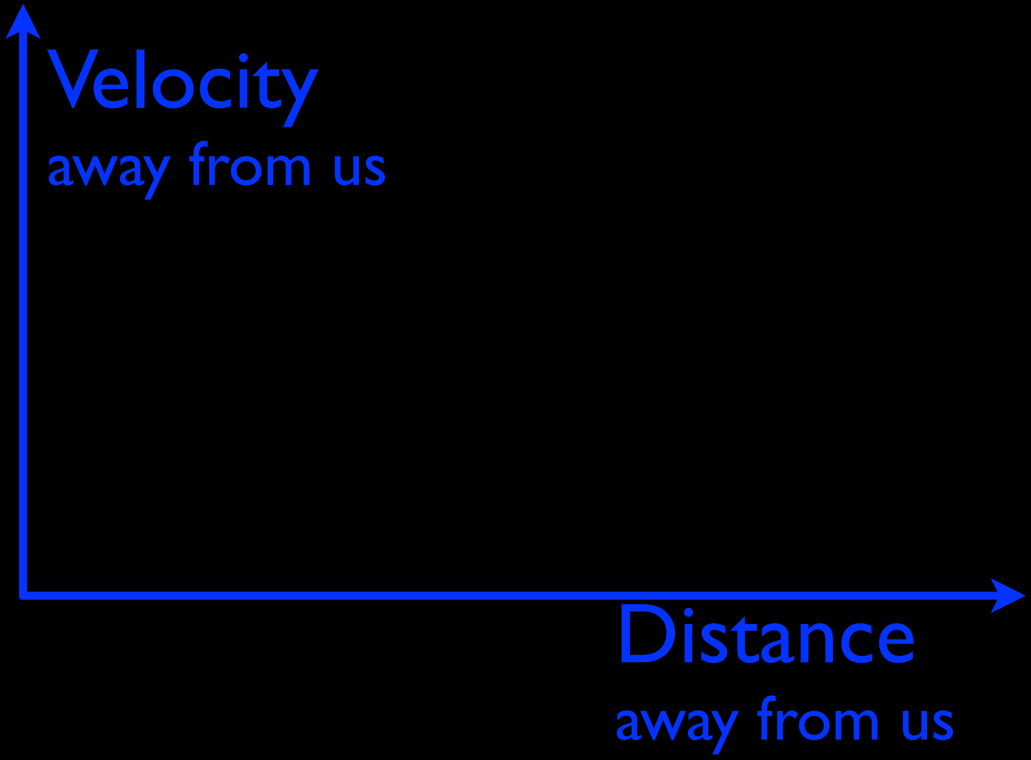
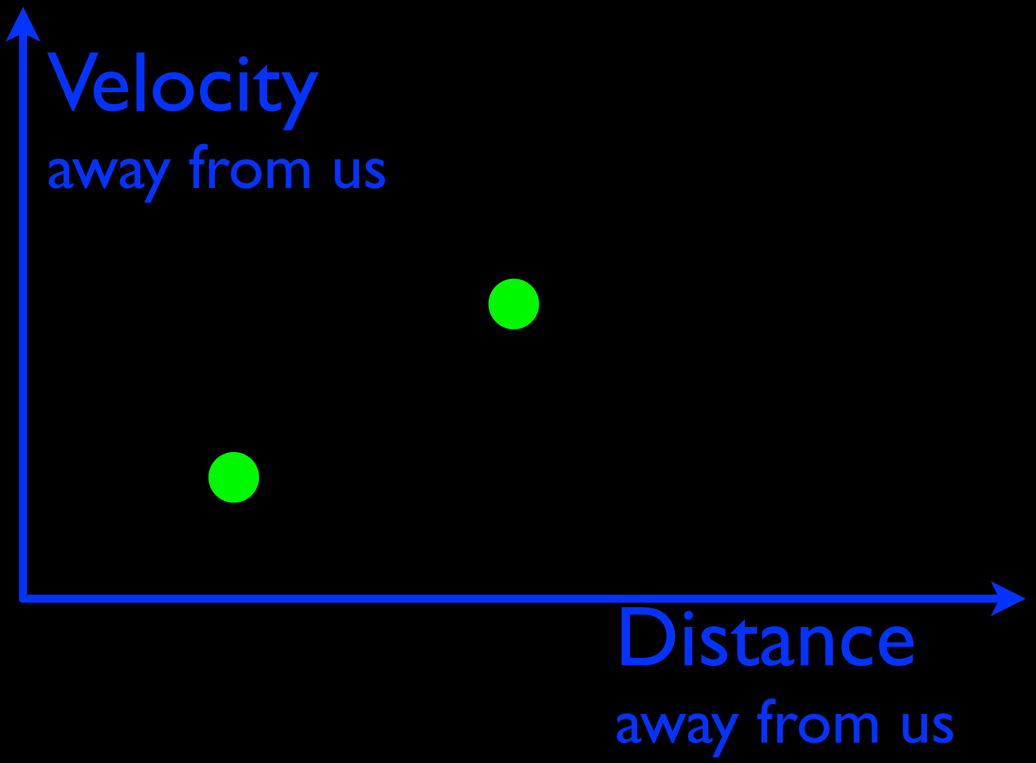
Distance

Velocity

Our Galaxy
(Milky Way)


Velocity
away from us
Distance
away from us


Velocity
away from us
Distance
away from us

The original **Hubble Diagram**

"A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae" E.Hubble (1929)

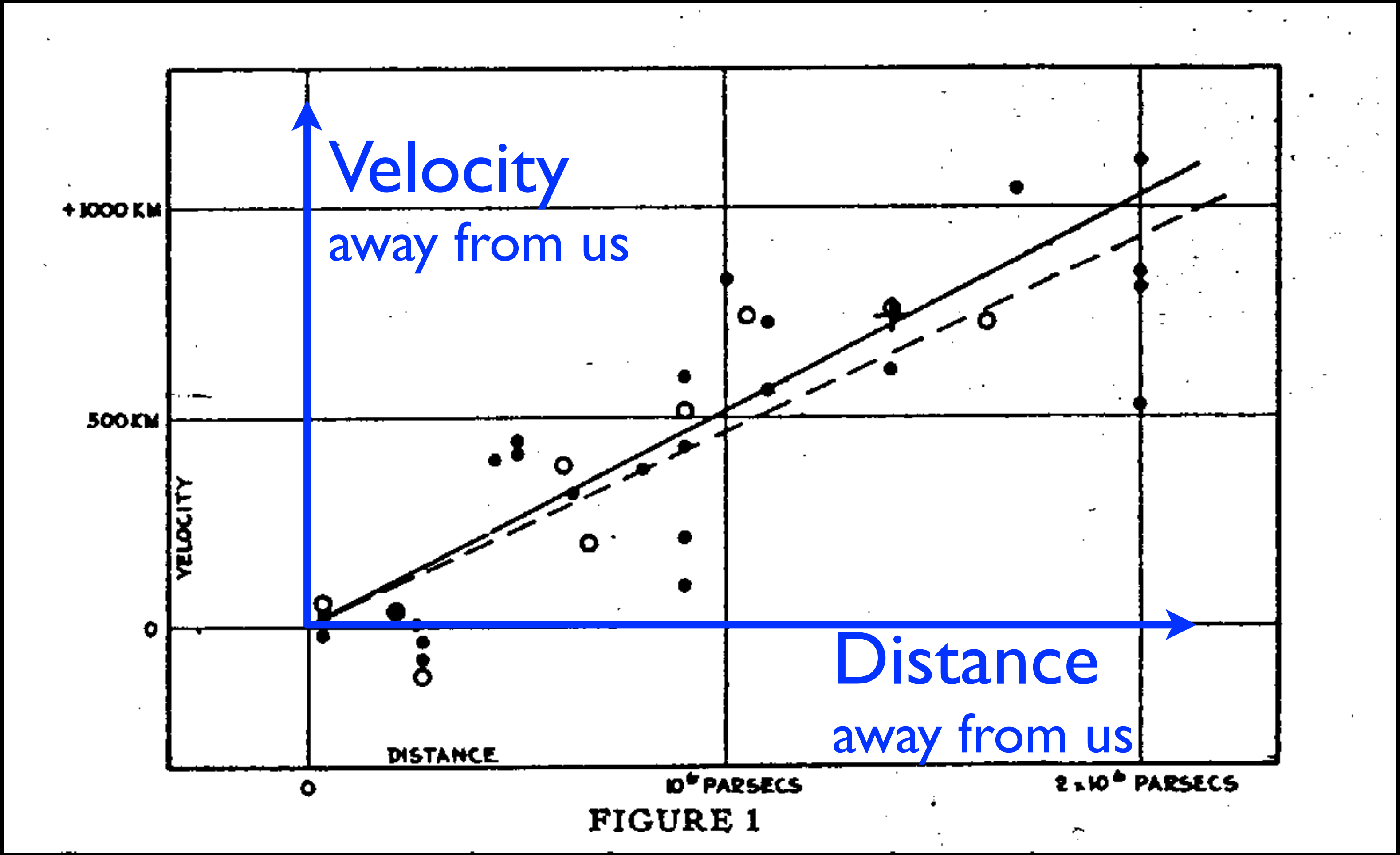


FIGURE 1

The original Hubble Diagram

"A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae"
E.Hubble (1929)

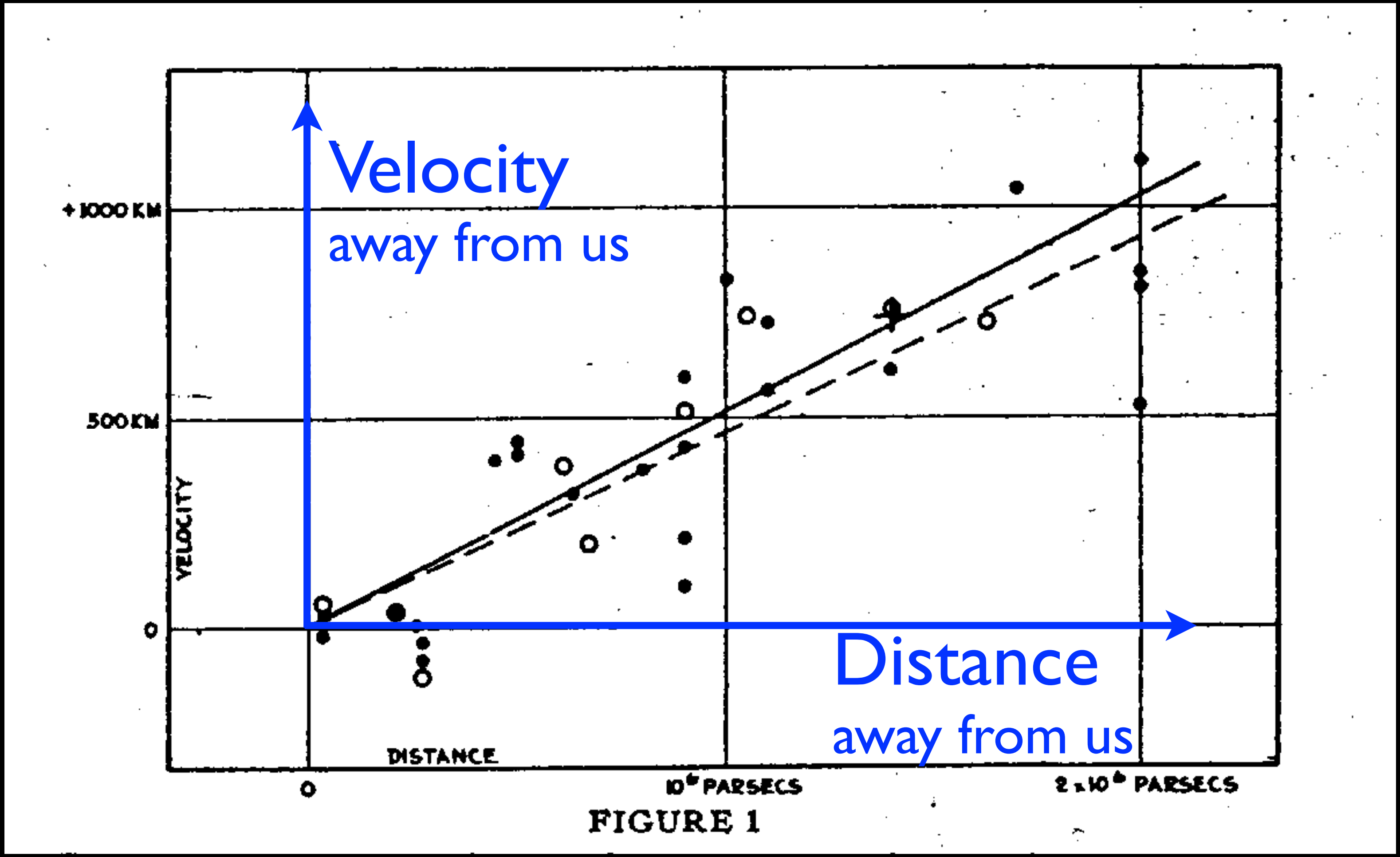


FIGURE 1

Edwin Hubble
American

Galaxies outside Milky Way

The original Hubble Diagram

“A Relation Between Distance and Radial Velocity Among Extra-Galactic Nebulae”
E.Hubble (1929)

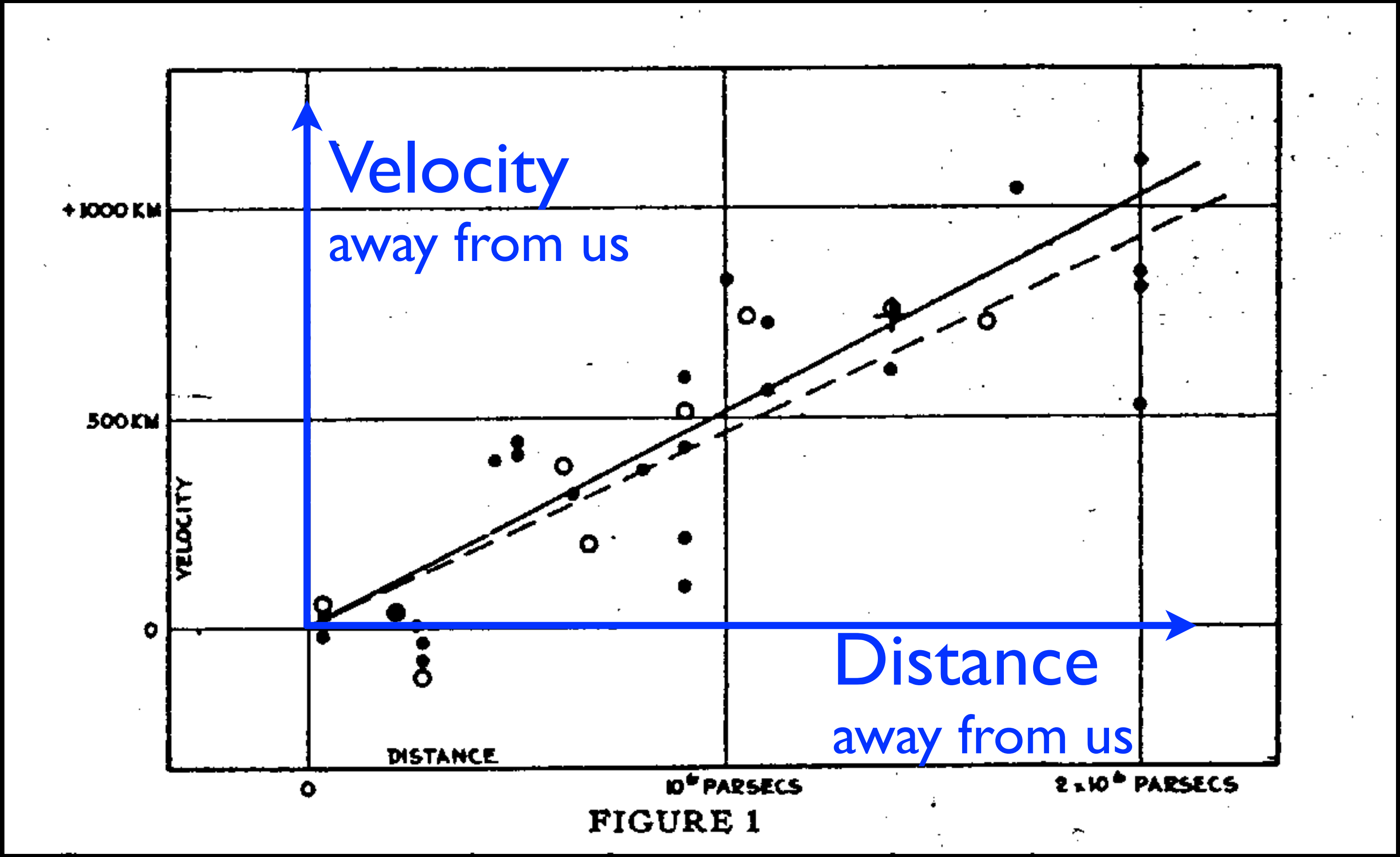


FIGURE 1

Edwin Hubble
American

Galaxies outside Milky Way

Henrietta Leavitt
American

Distances via variable stars

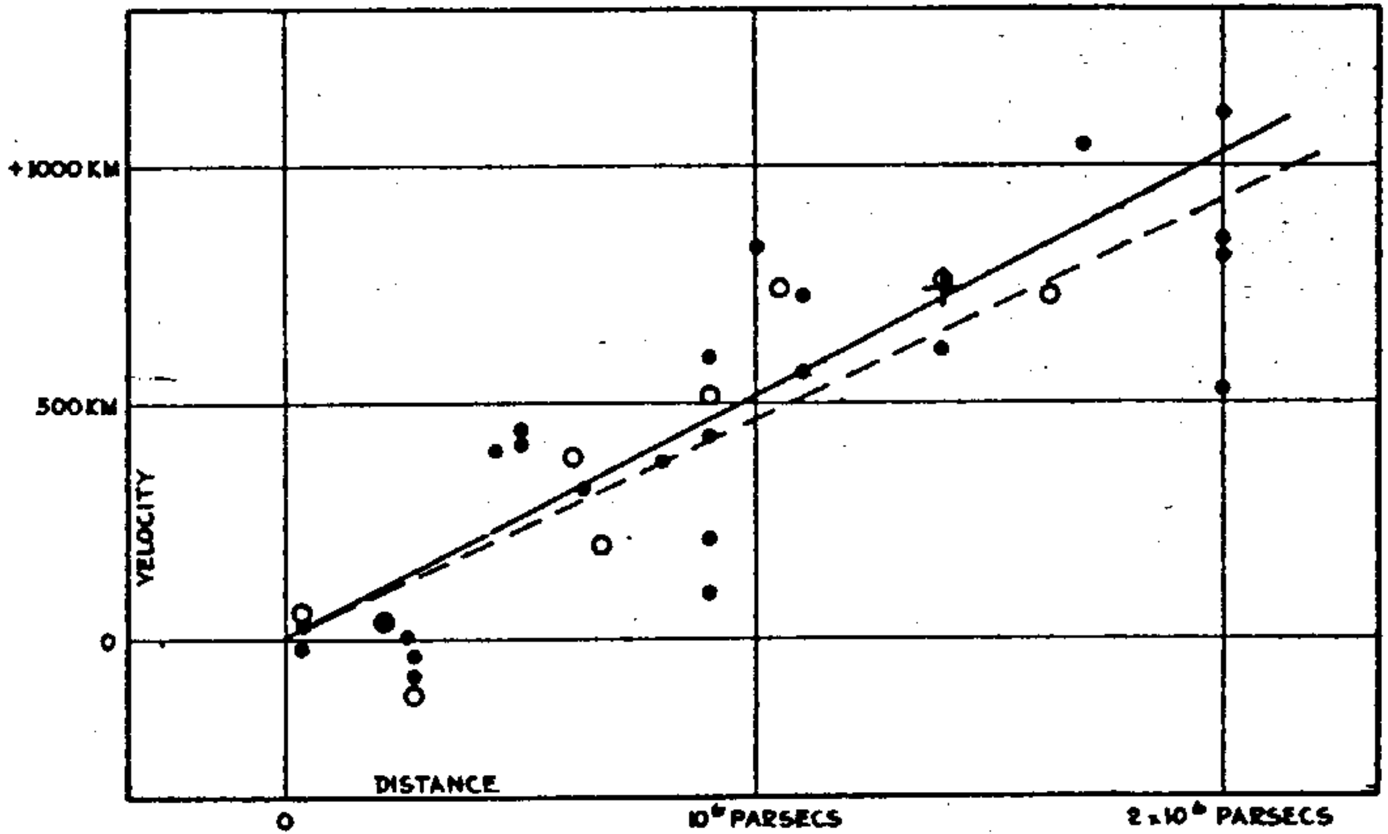
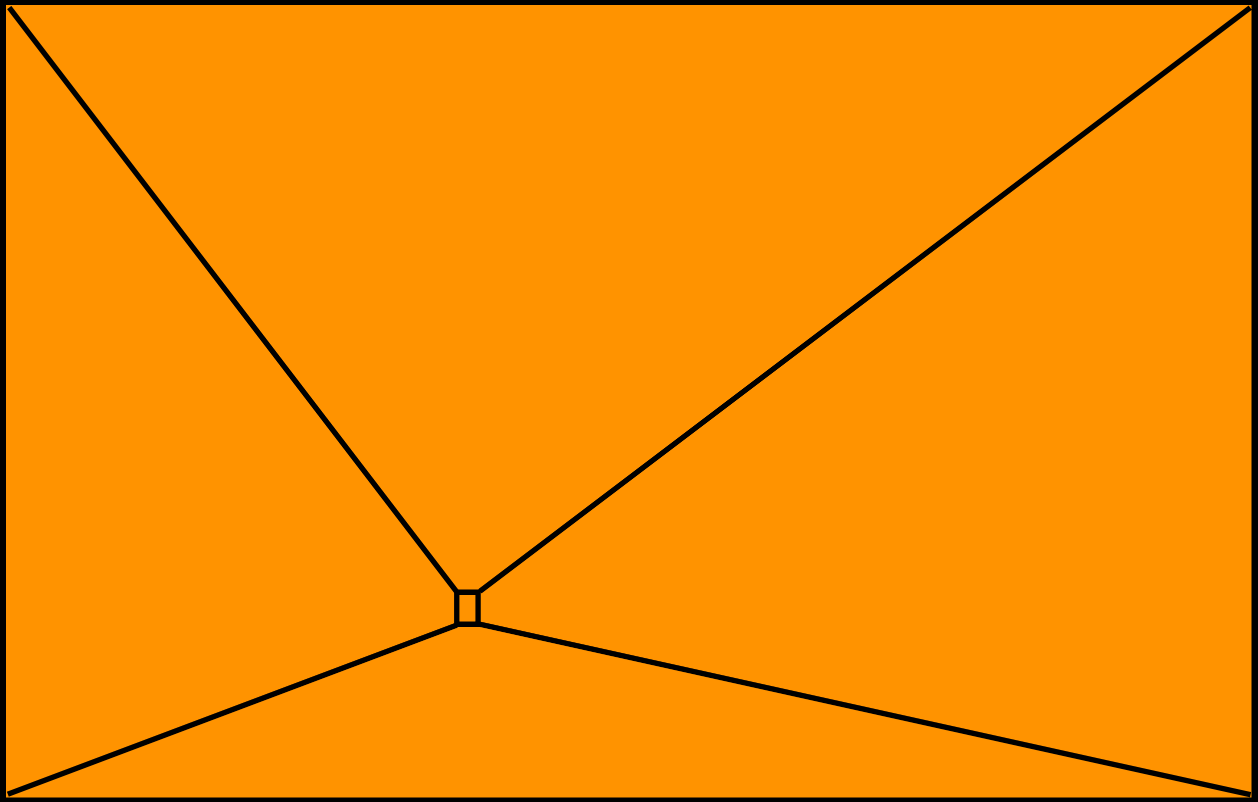
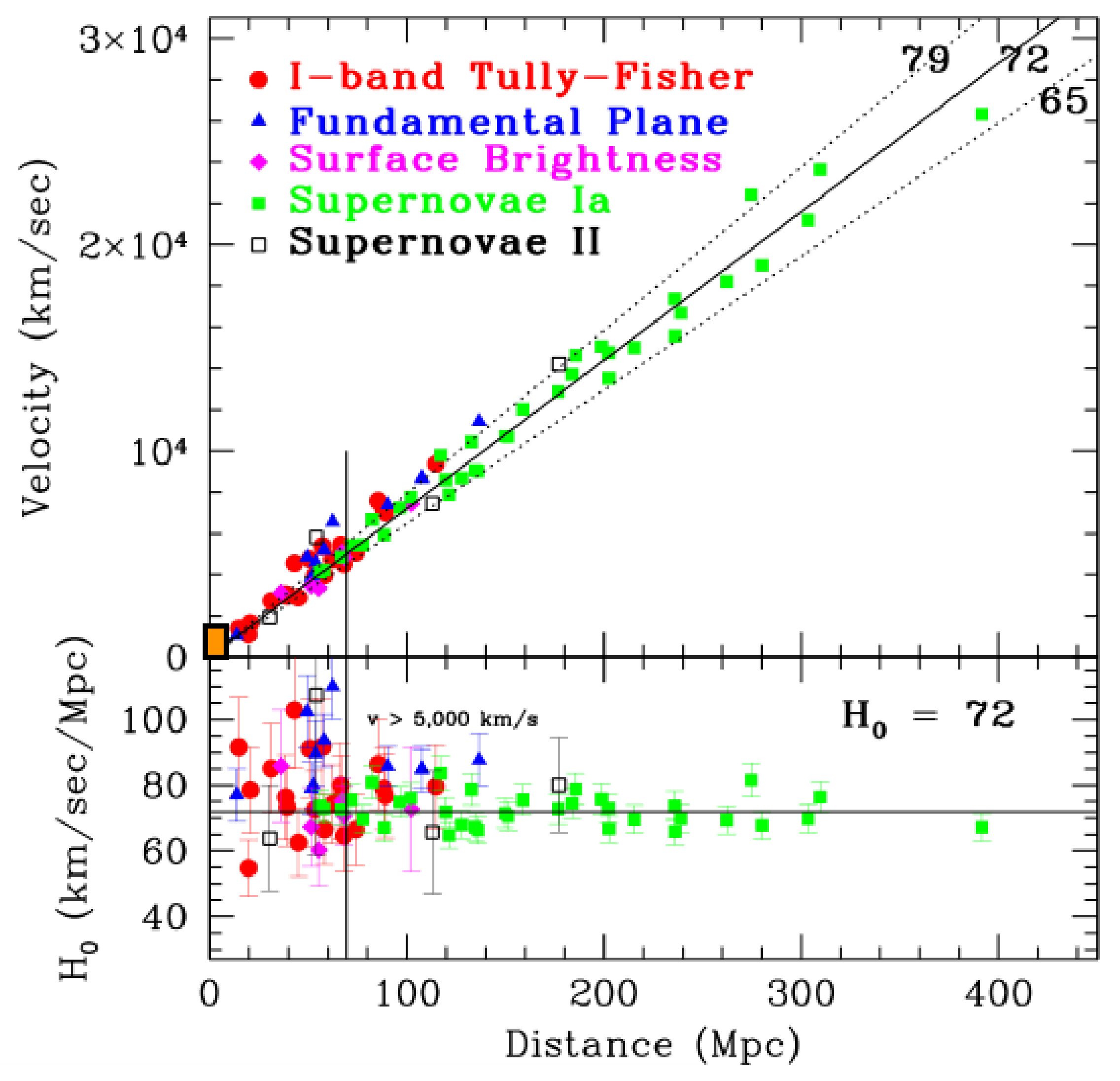
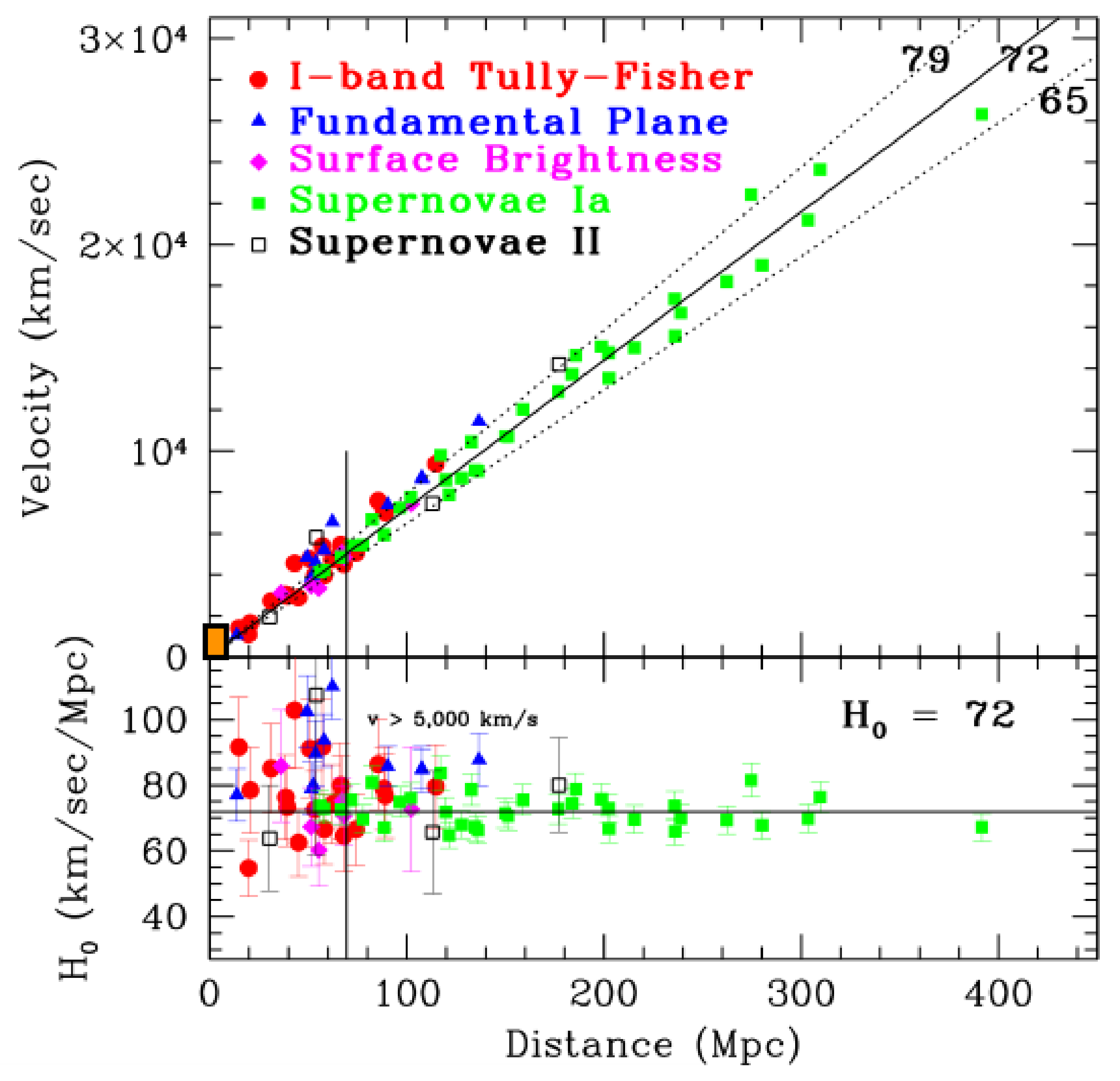

+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10⁶ PARSECS
2 x 10⁶ PARSECS

FIGURE 1





Freedman, et al. Astrophys. J. 553, 47 (2001)



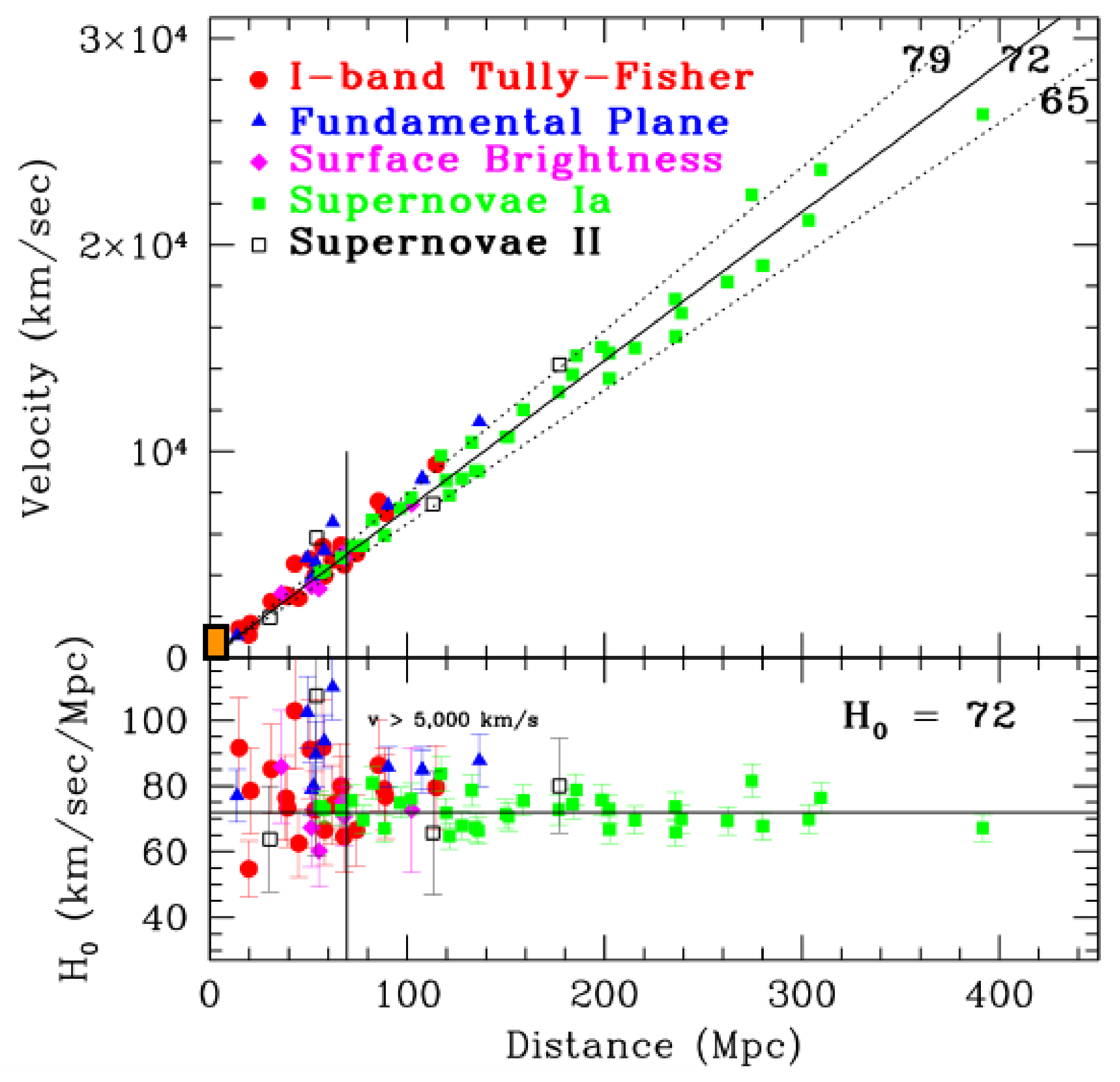
Freedman, et al. Astrophys. J. 553, 47 (2001)

W. Freedman
Canadian

Modern Hubble constant (2001)

Hubble Relation

$$v = H_0\, d$$



Freedman, et al. Astrophys. J. 553, 47 (2001)

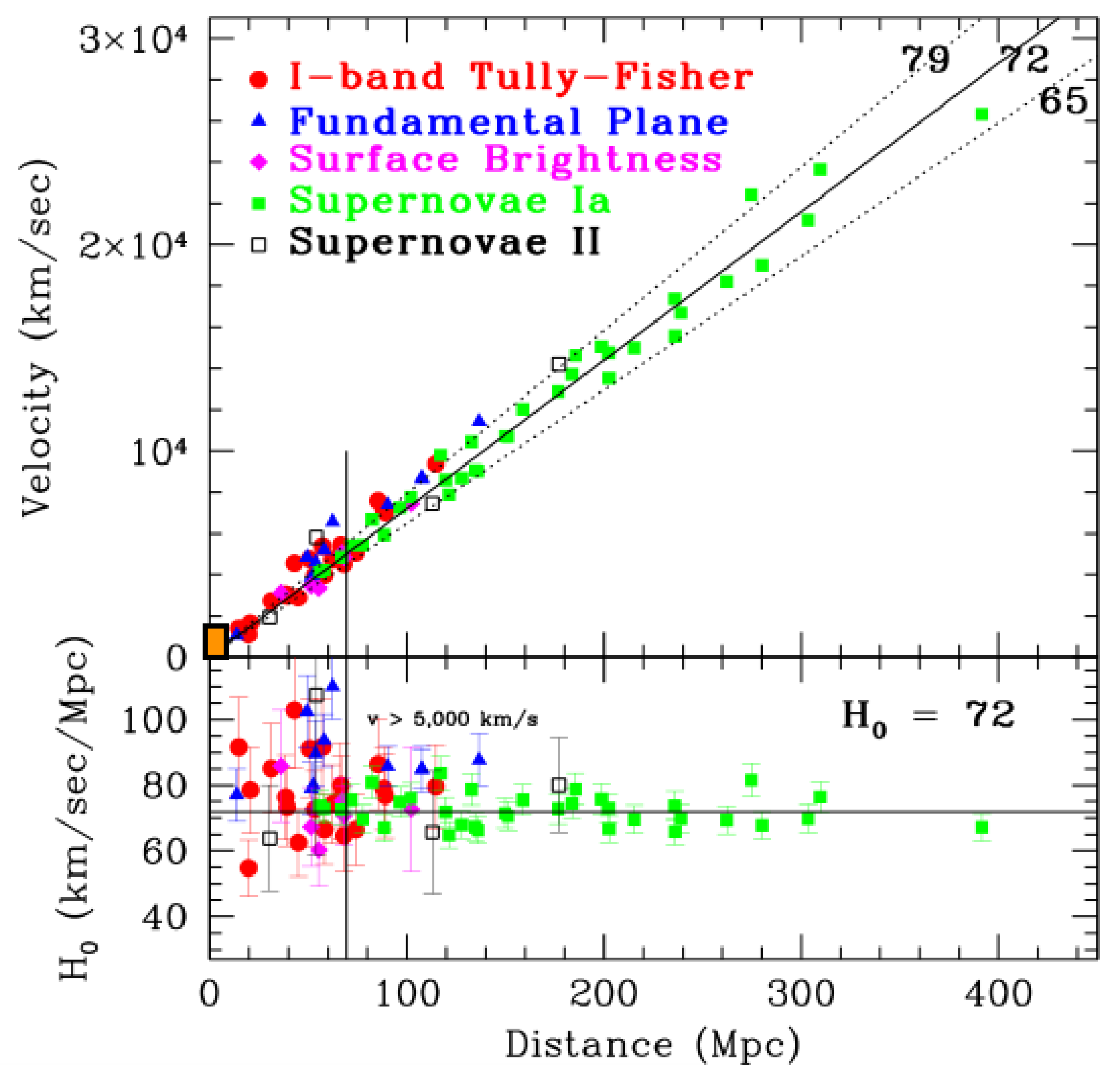
W. Freedman
Canadian

Modern Hubble constant (2001)

Hubble Relation

$$v = H_0 \, d$$

Year	H_0 km/sec/Mpc
1929	~500
2001	72 +/- 7



Freedman, et al. Astrophys. J. 553, 47 (2001)

W. Freedman
Canadian

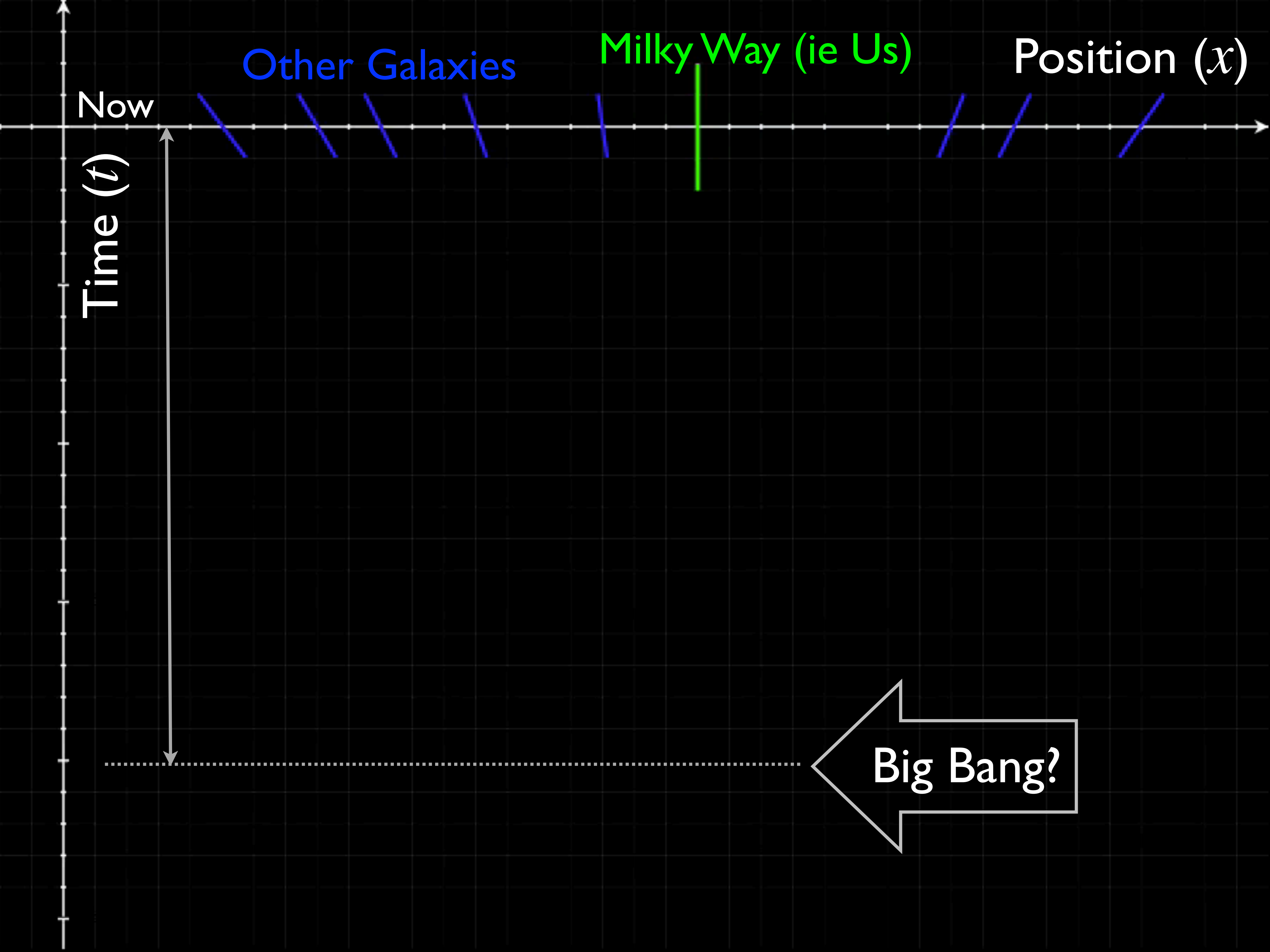
Modern Hubble
constant (2001)

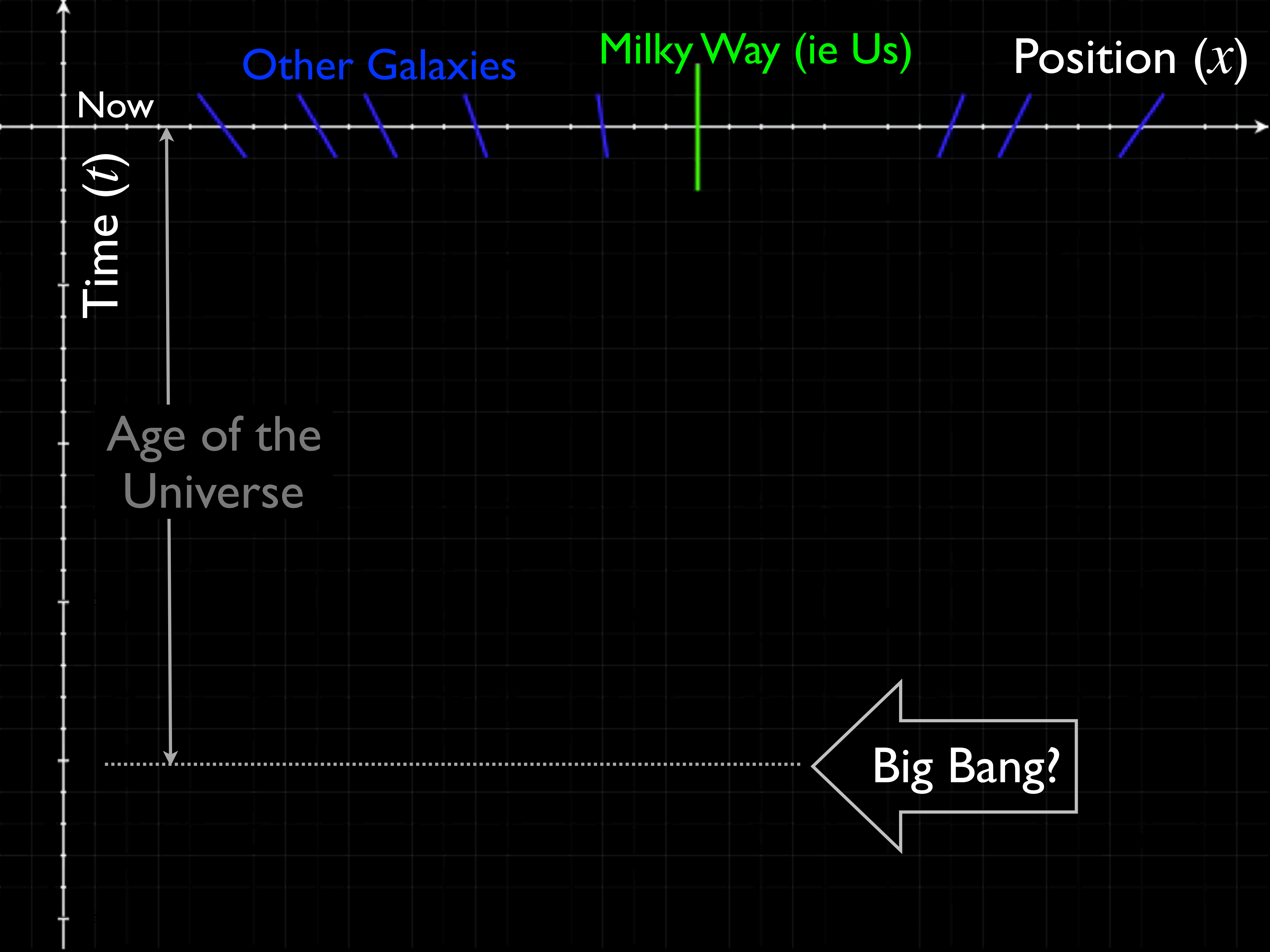

Milky Way (ie Us)
Position (x)
Now
Time (t)


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)
Big Bang?



Other Galaxies

Milky Way (ie Us)

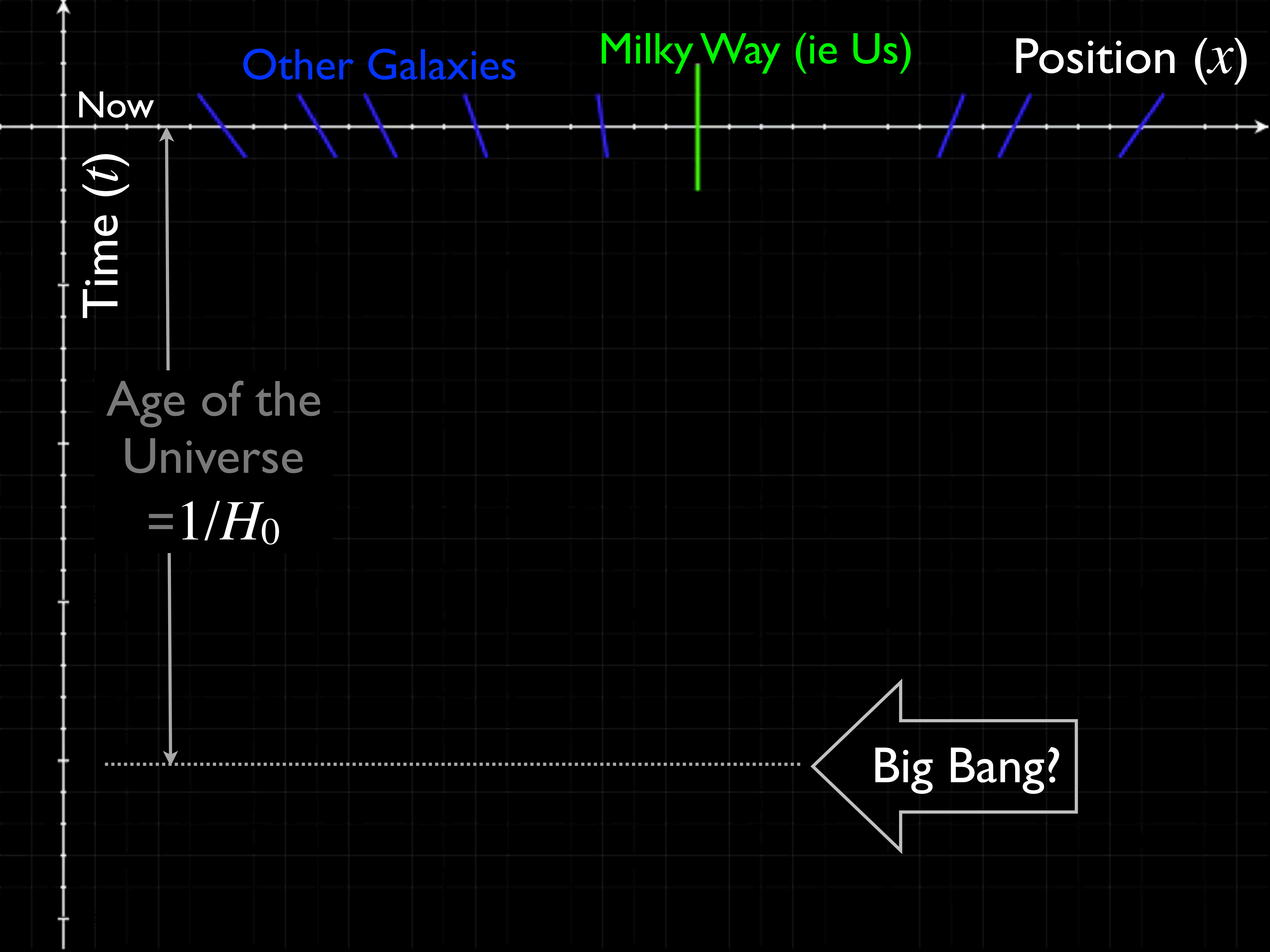
Position (x)

Now

Time (t)

Age of the Universe

Big Bang?



Other Galaxies

Milky Way (ie Us)

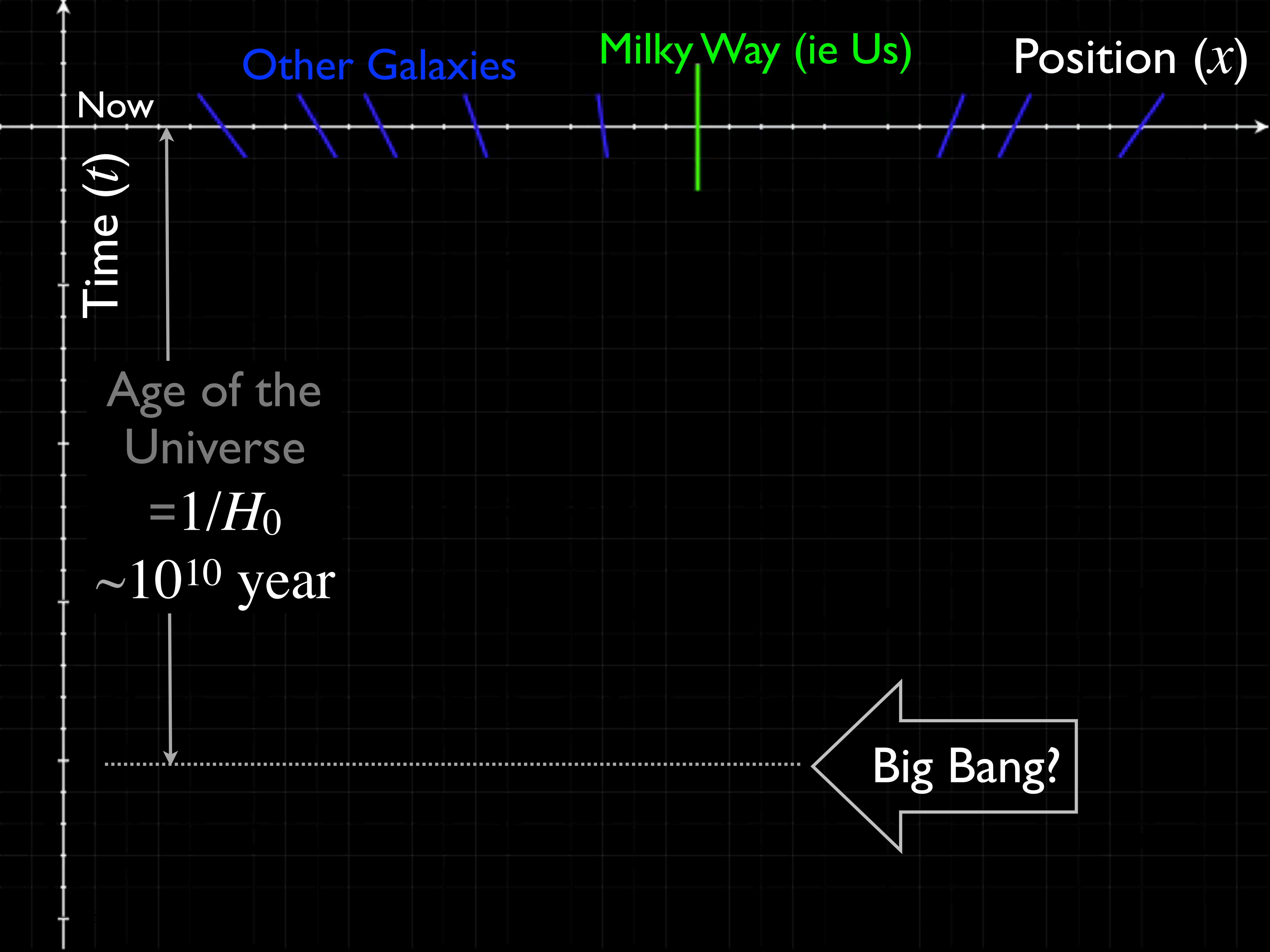
Position (x)

Now

Time (t)

Age of the Universe $=1/H_0$

Big Bang?



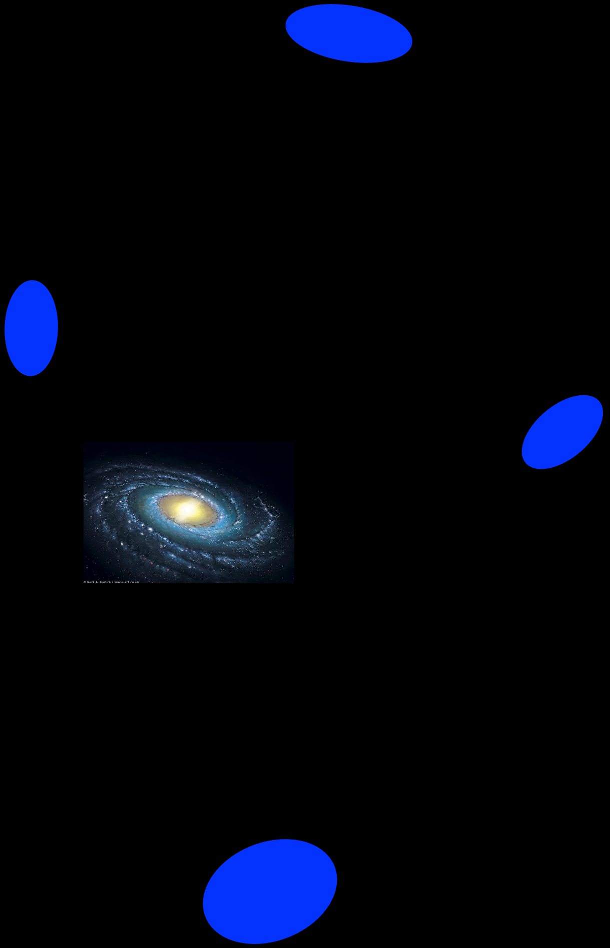
Age of the Universe

$=1/H_0$

$\sim 10^{10}$ year

Big Bang?

Now



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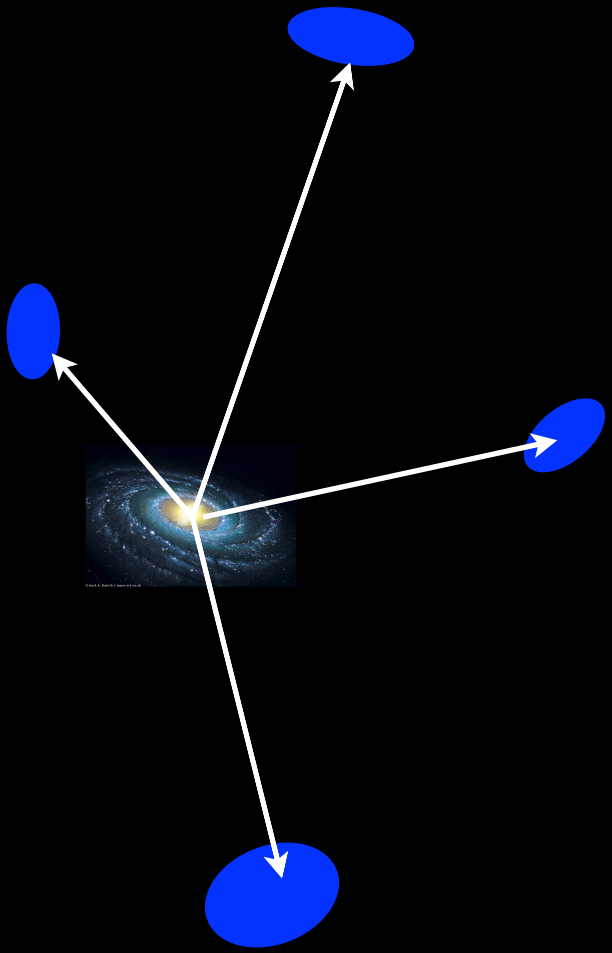
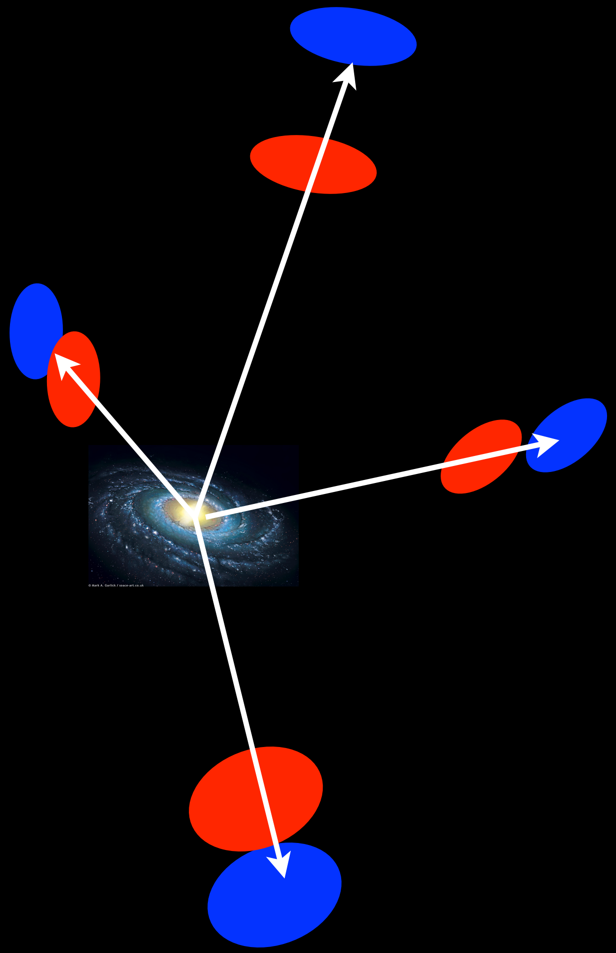
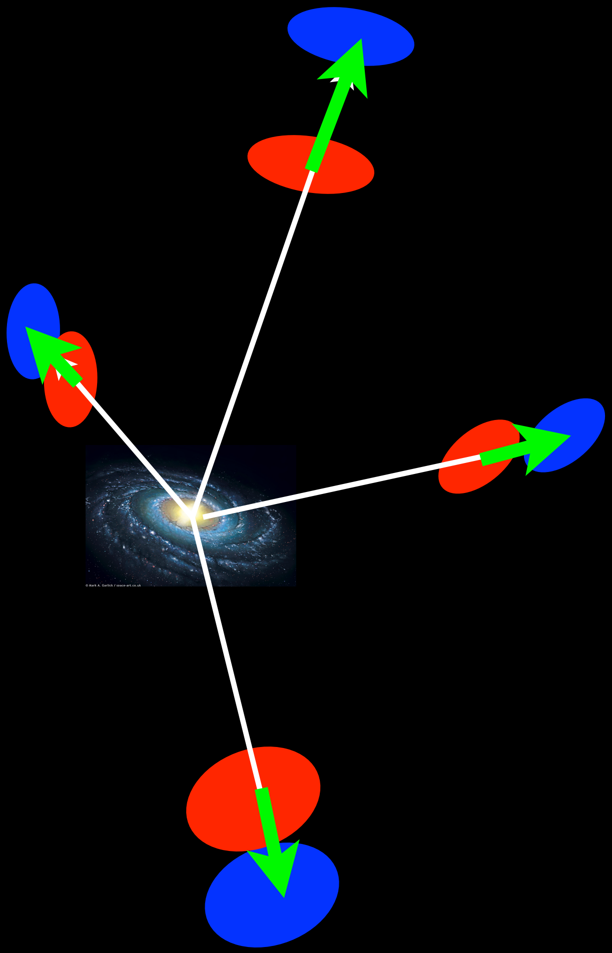
Now





Now

Earlier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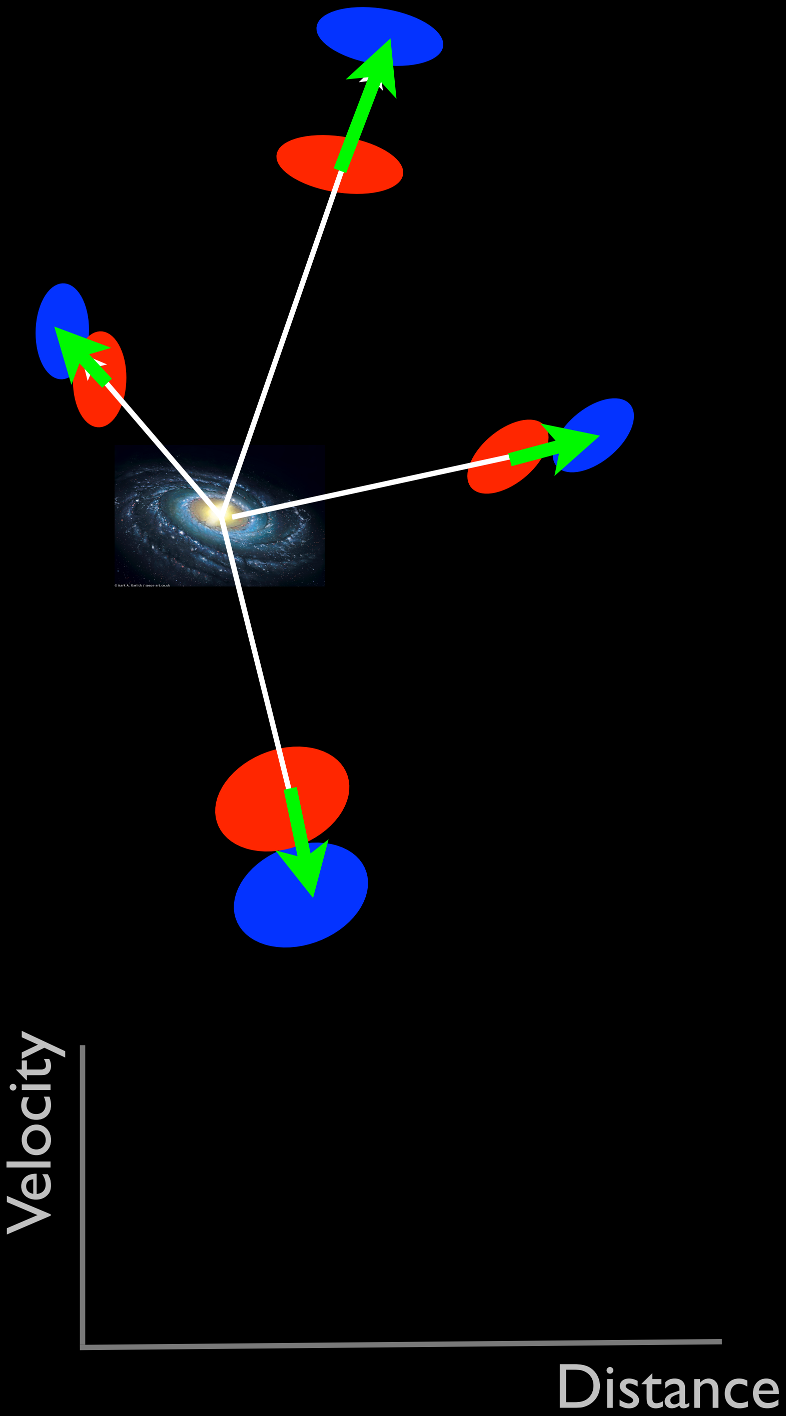
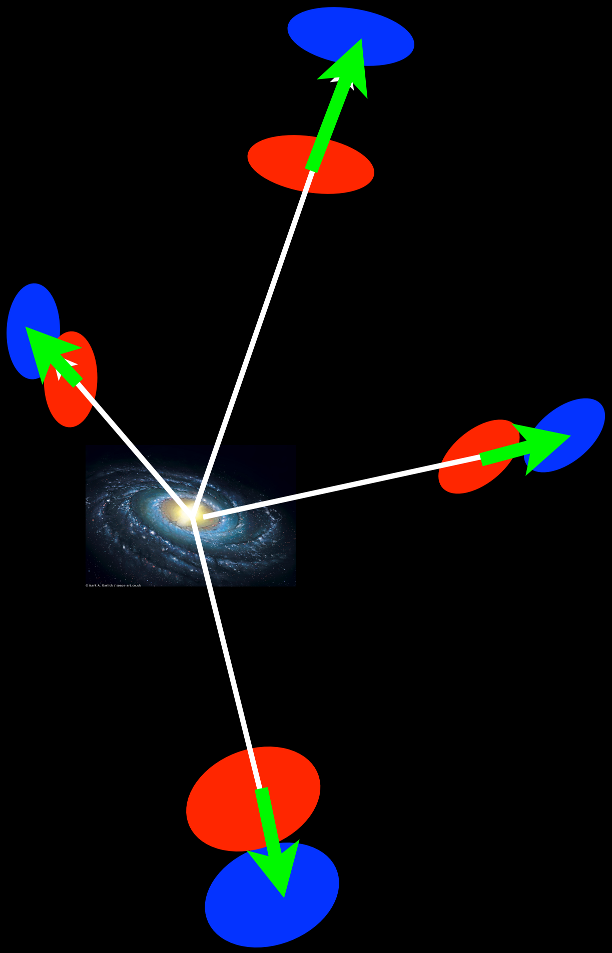
Now

Earlier

Now

Earlier





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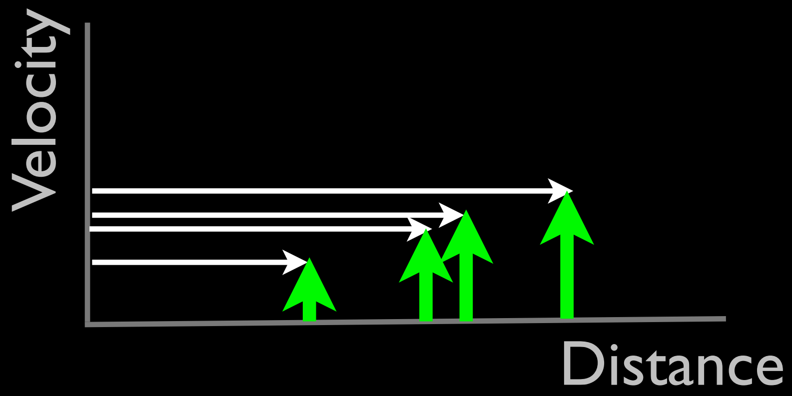

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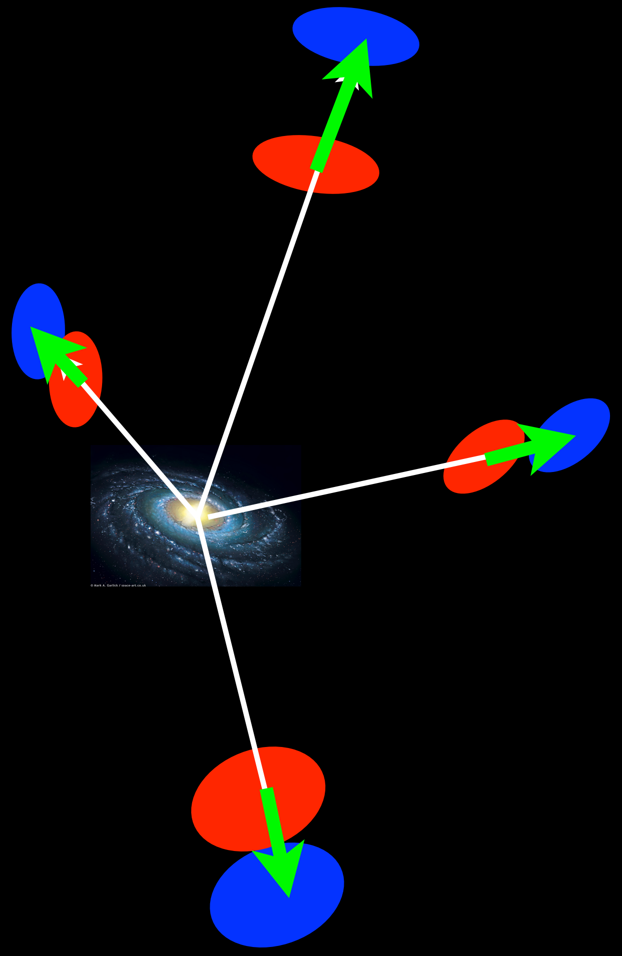

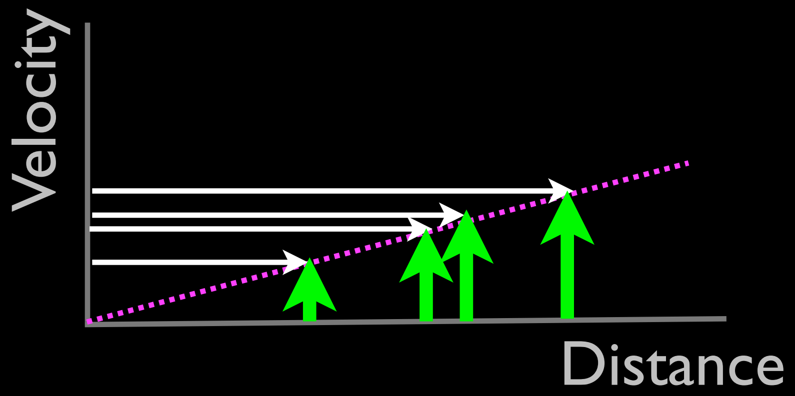

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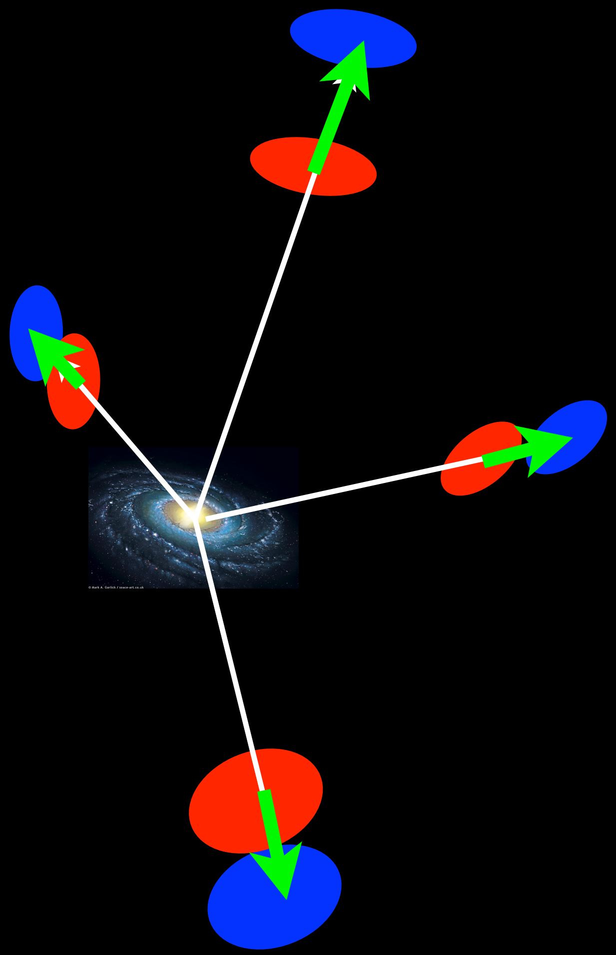

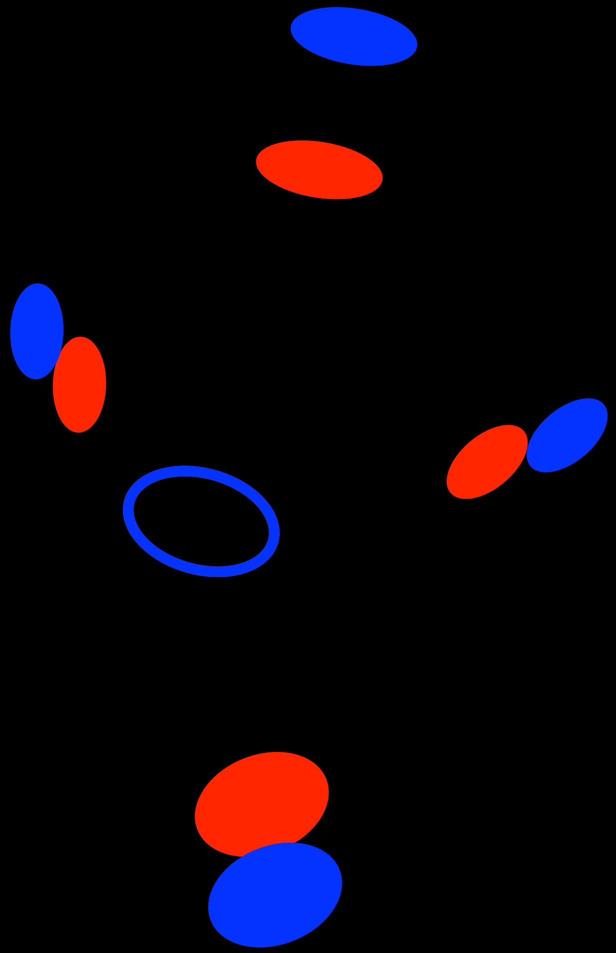

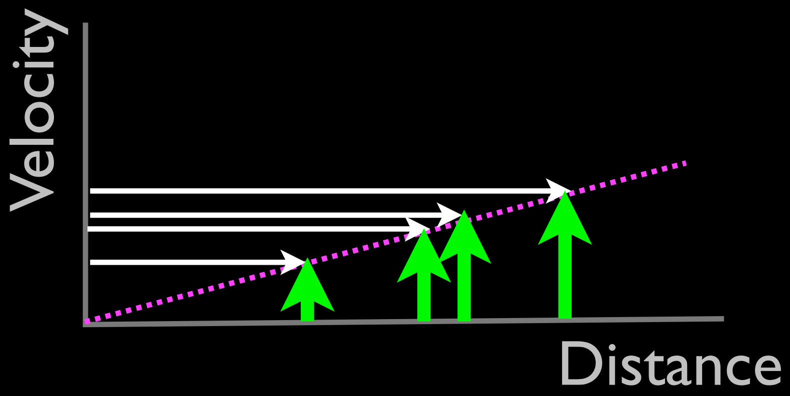

Now

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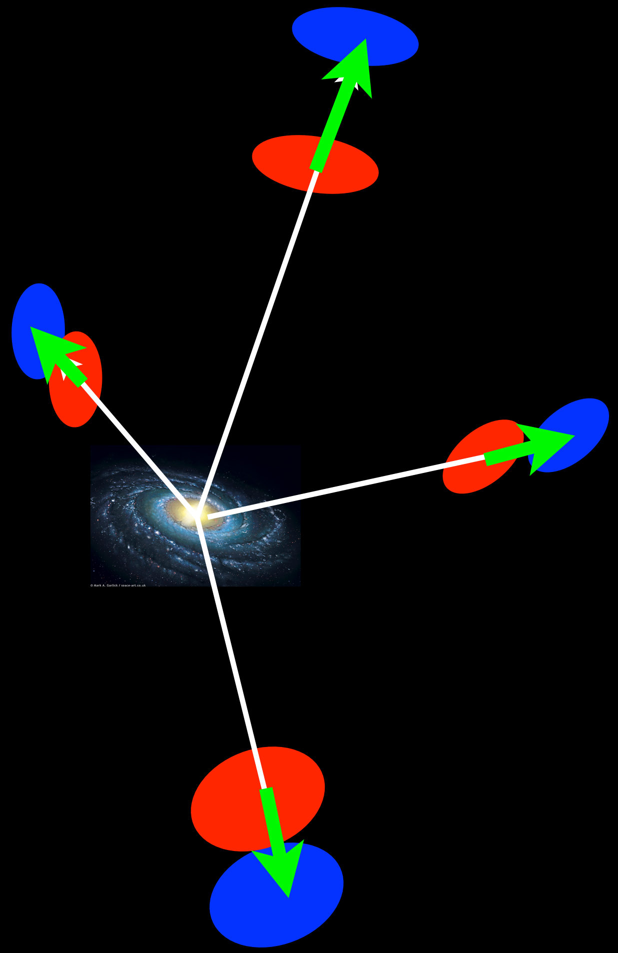

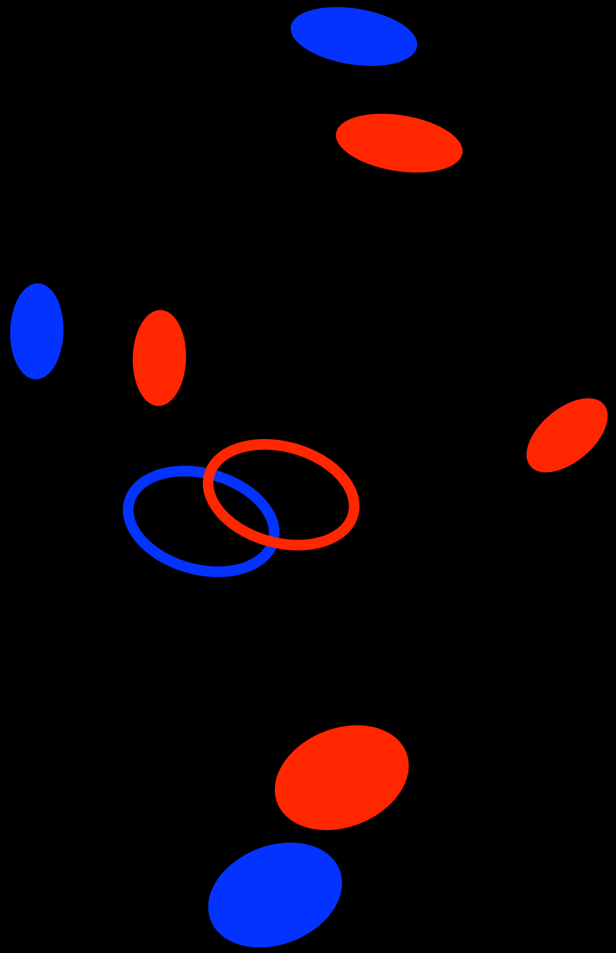

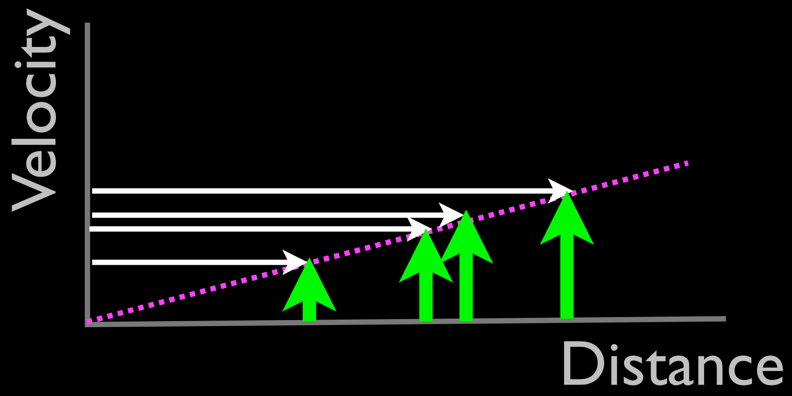

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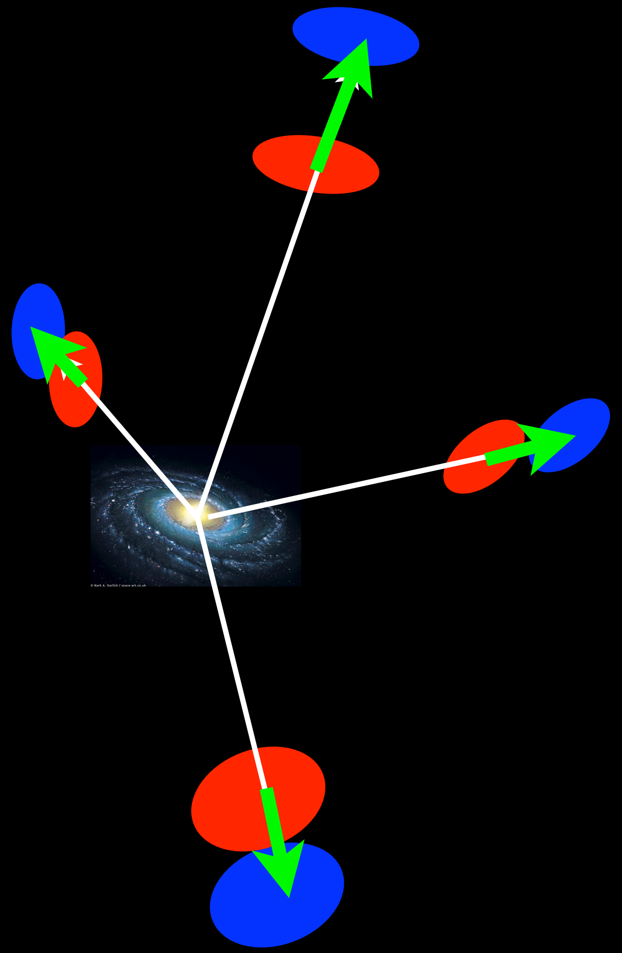

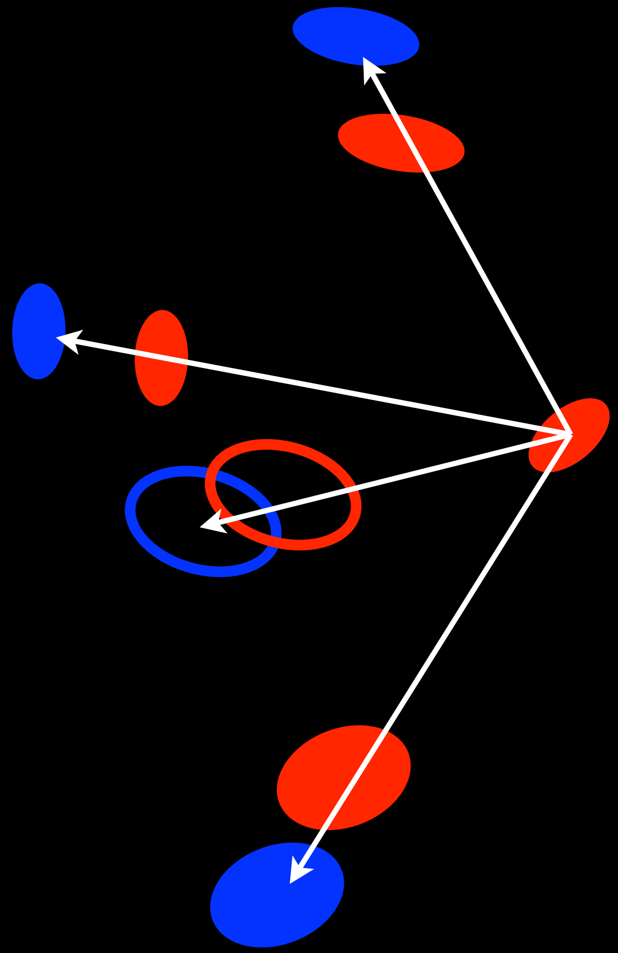

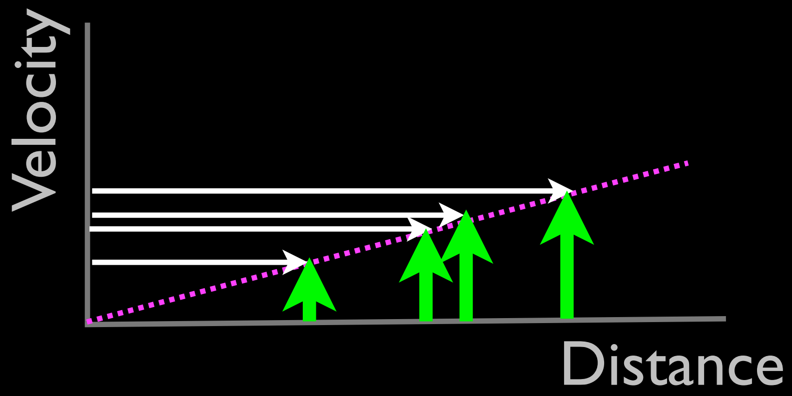

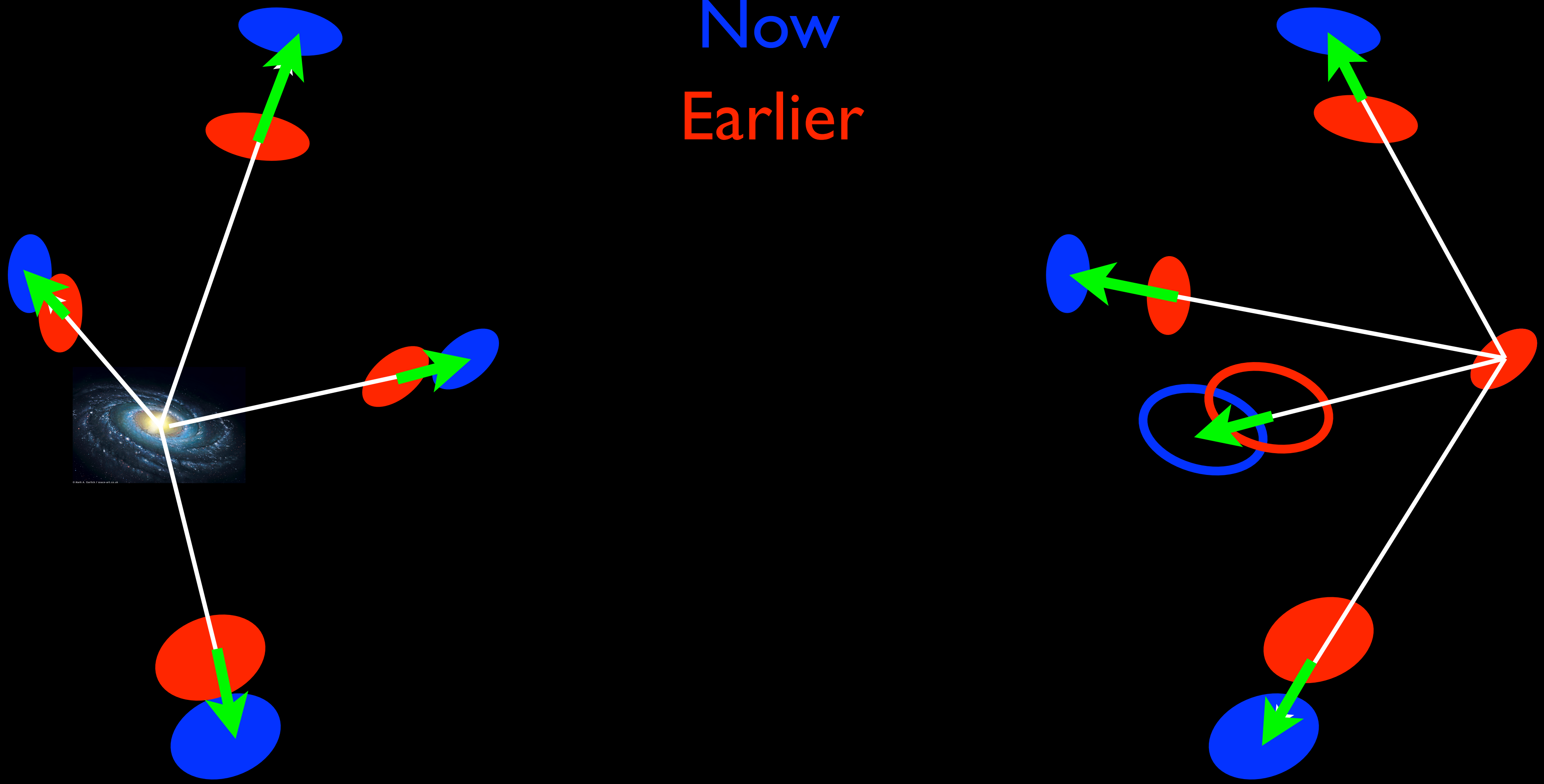

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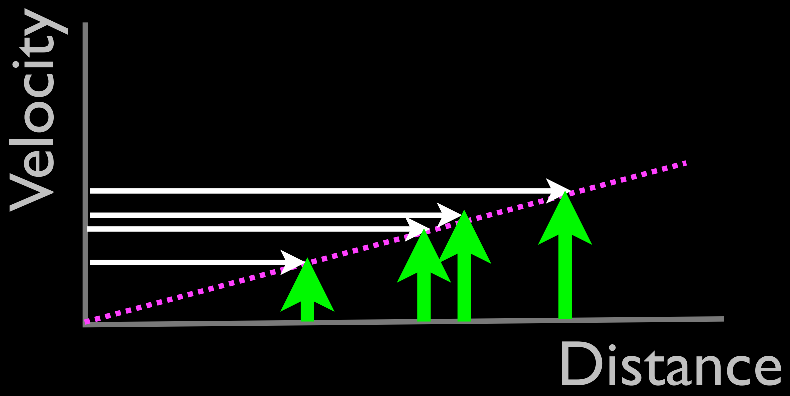

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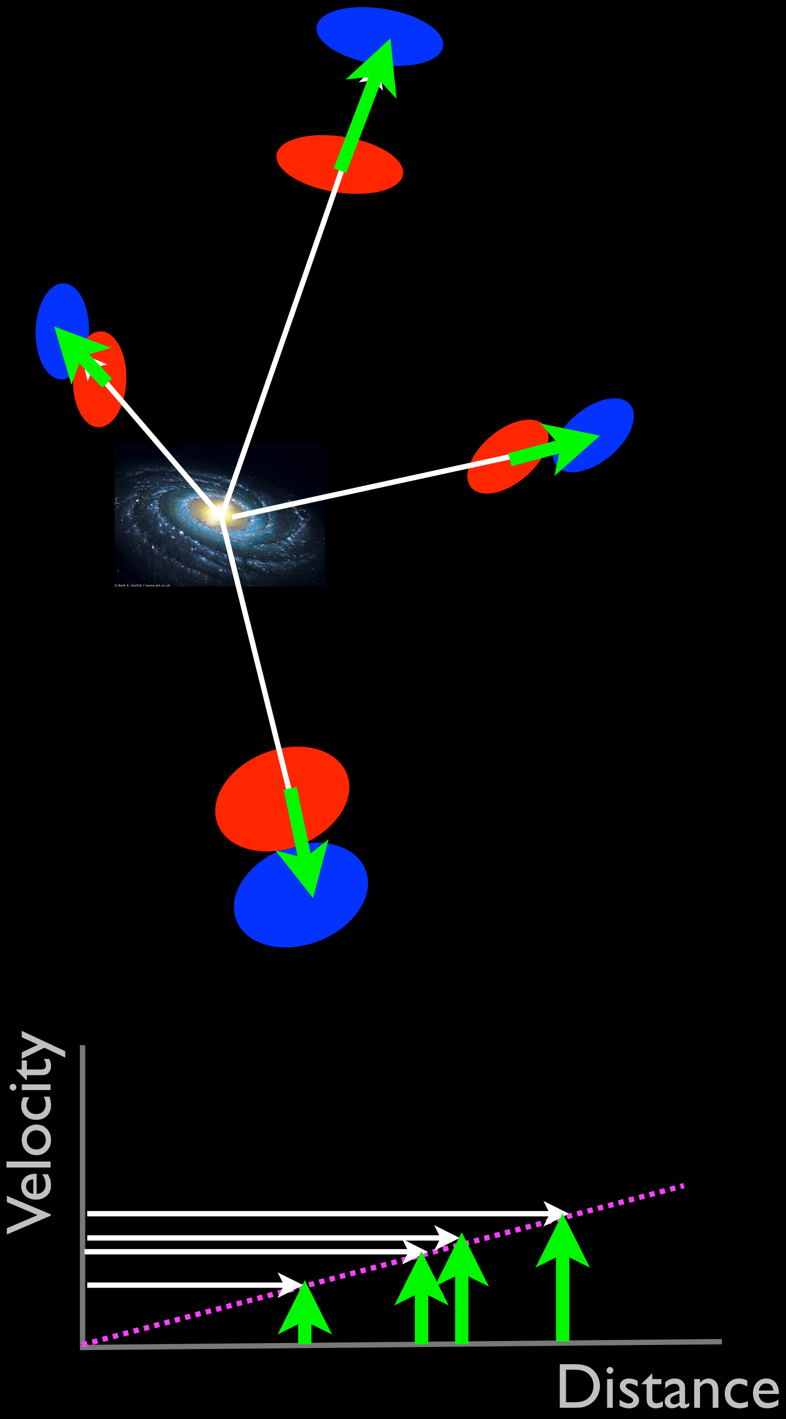
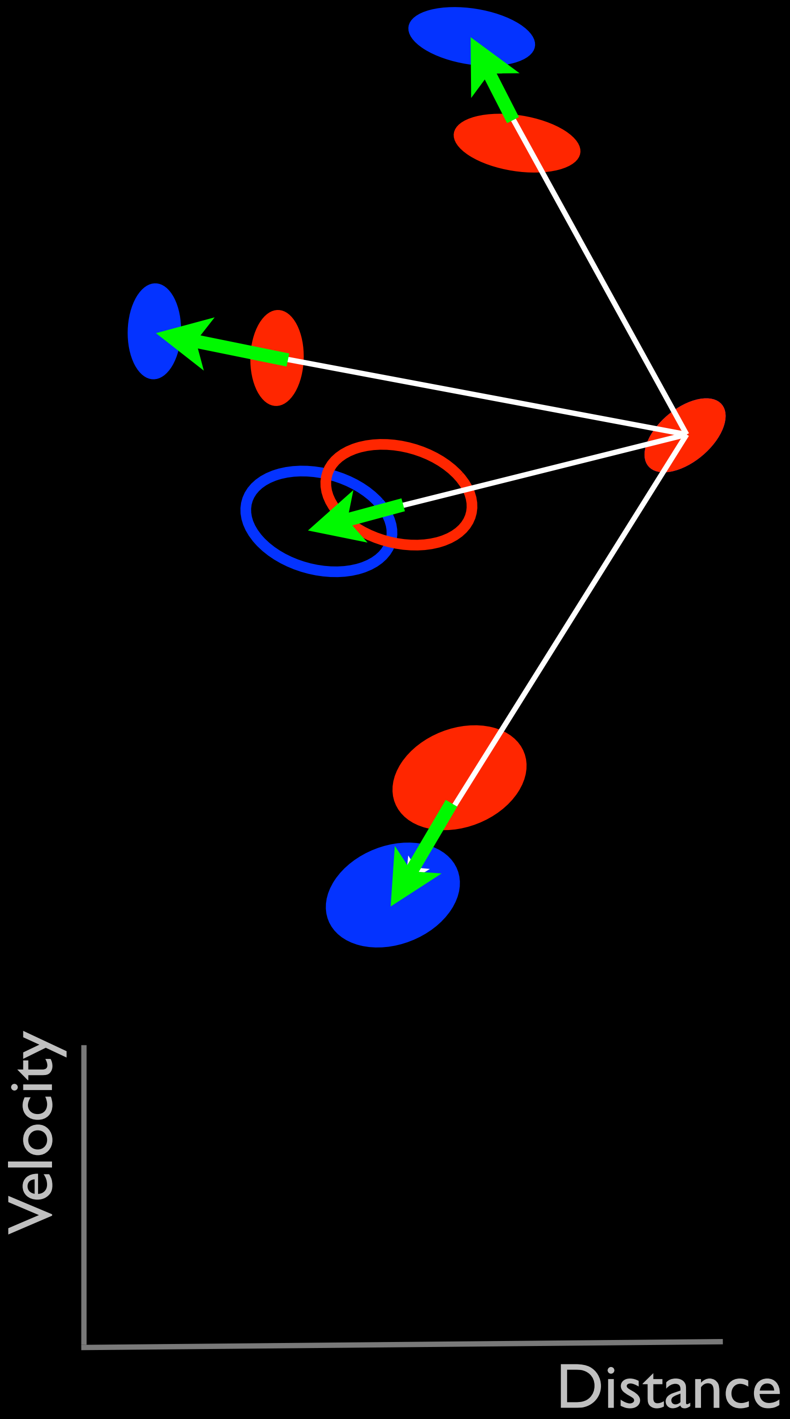
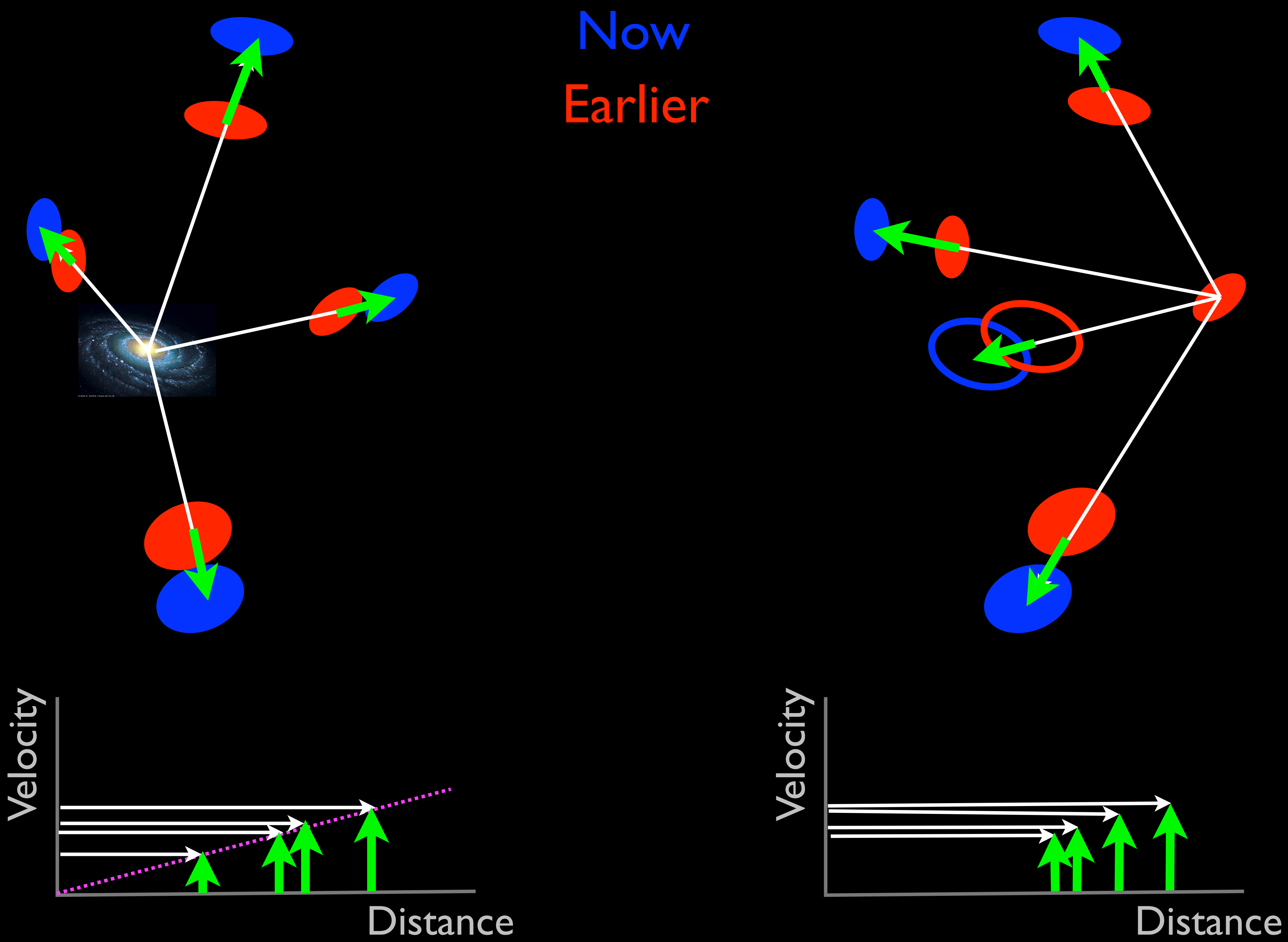
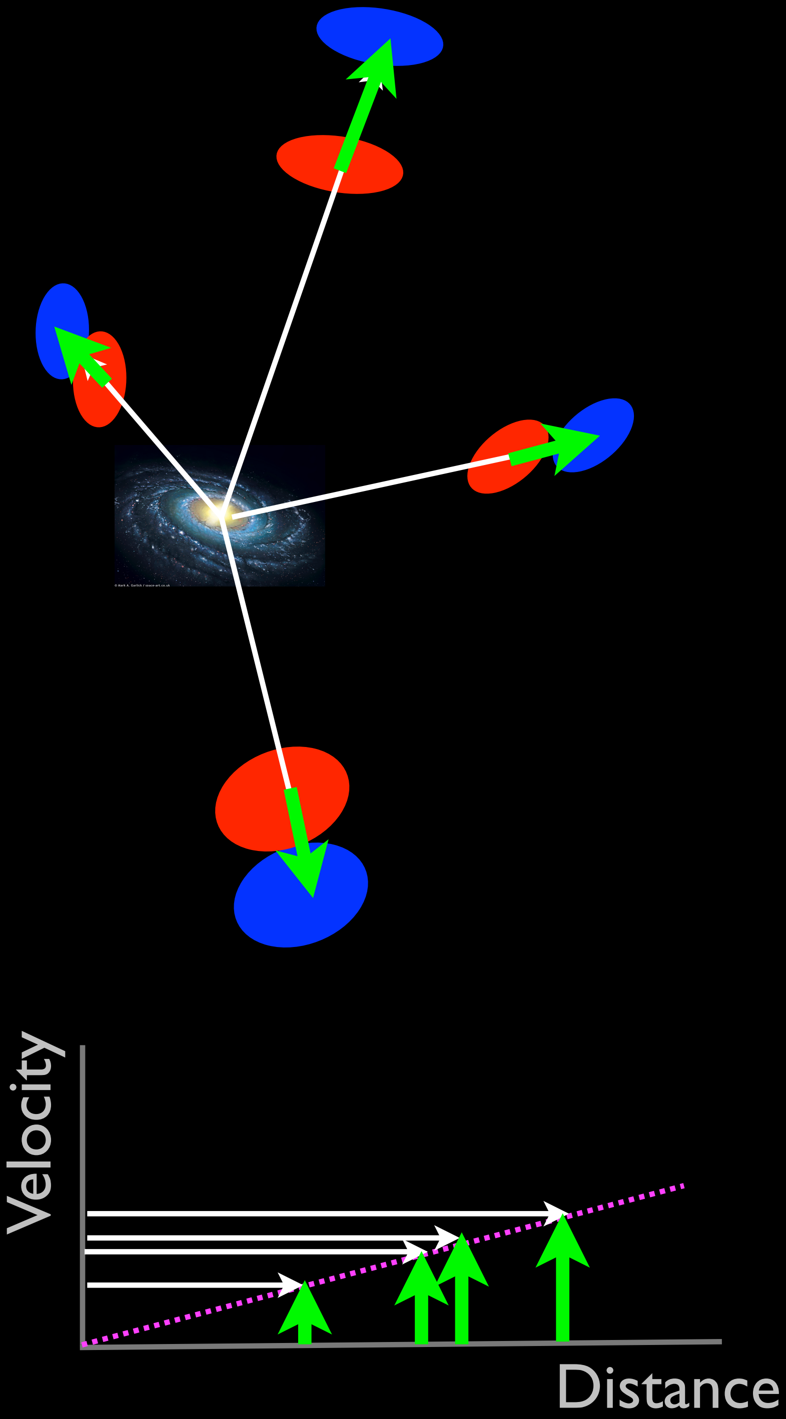


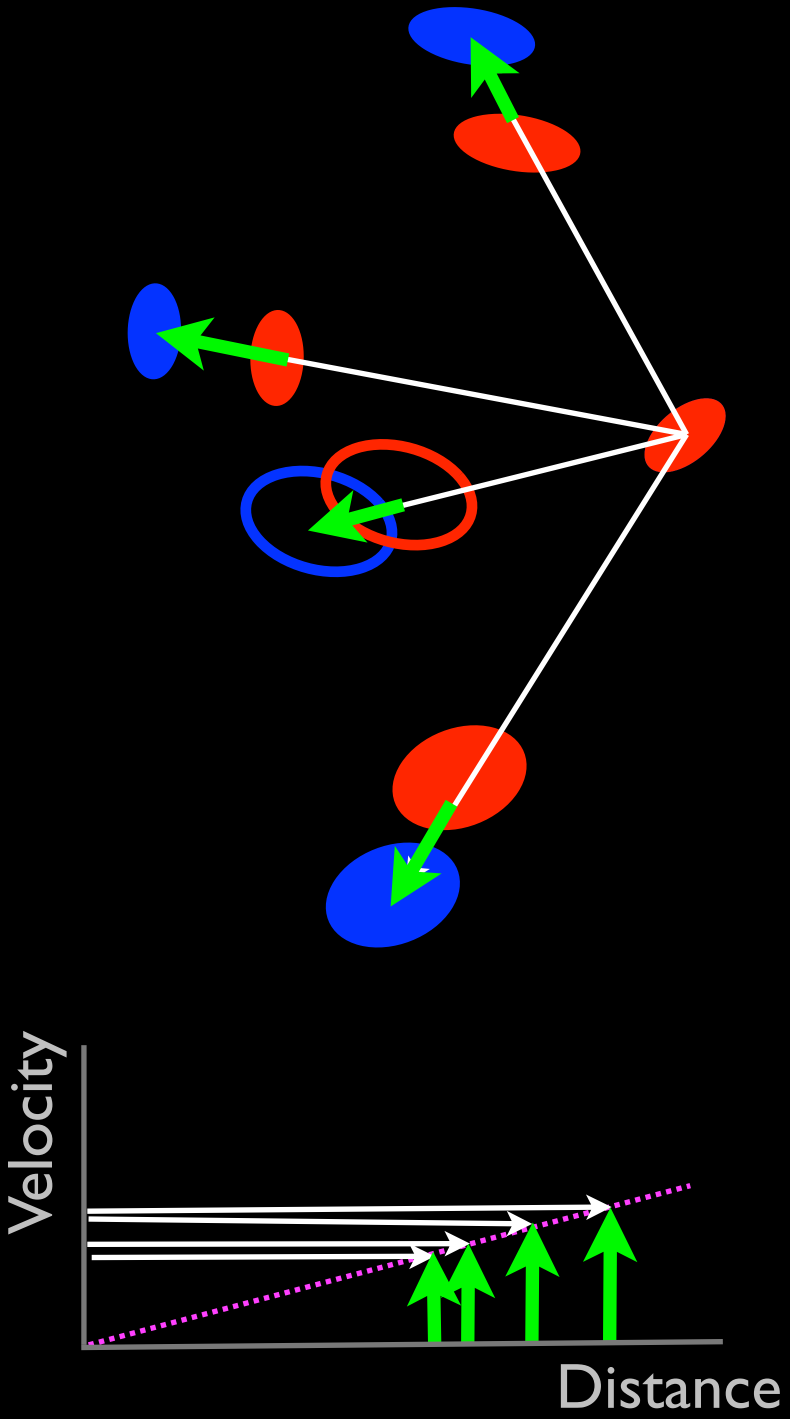



Now
Earlier
Velocity
Distance
Velocity
Distance

Now

Earlier





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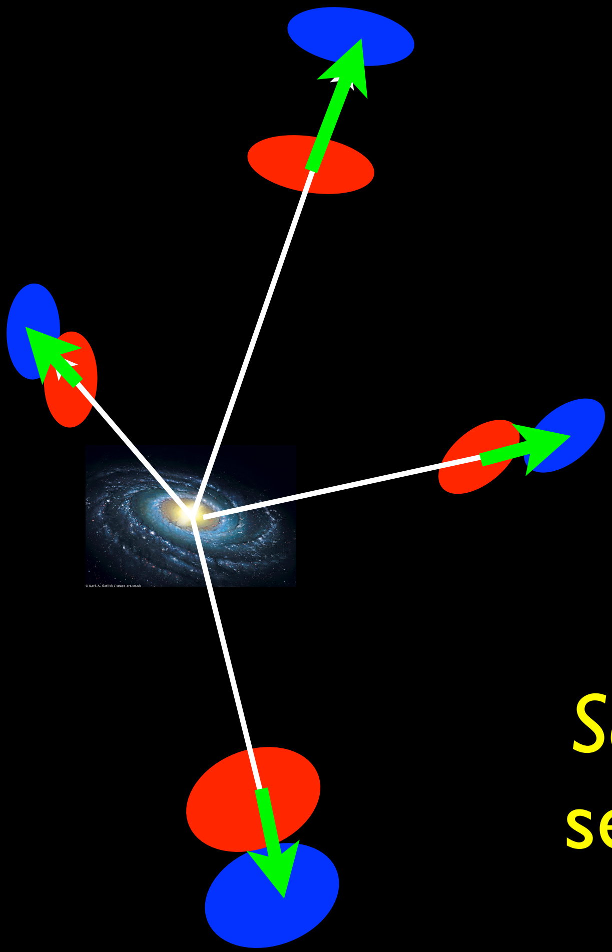
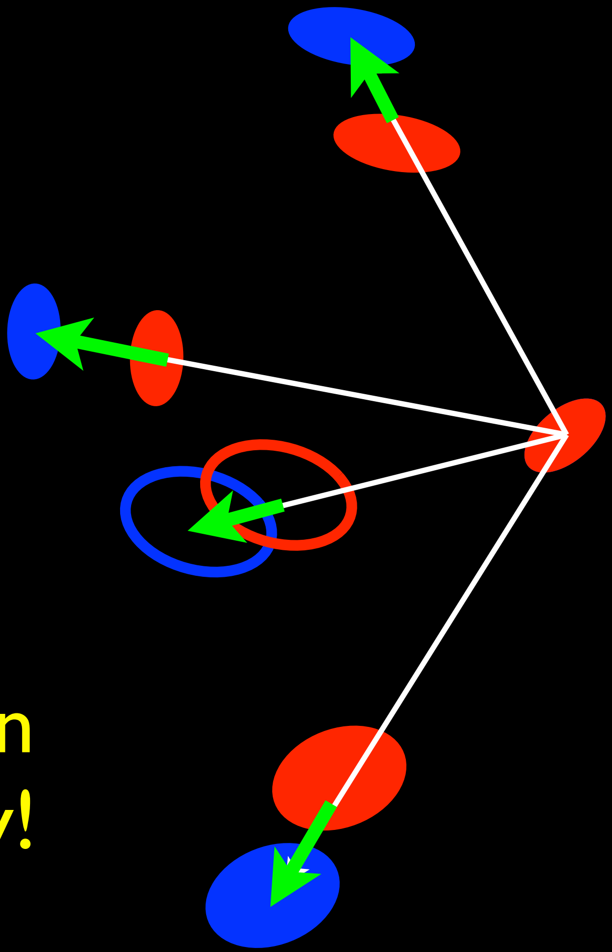
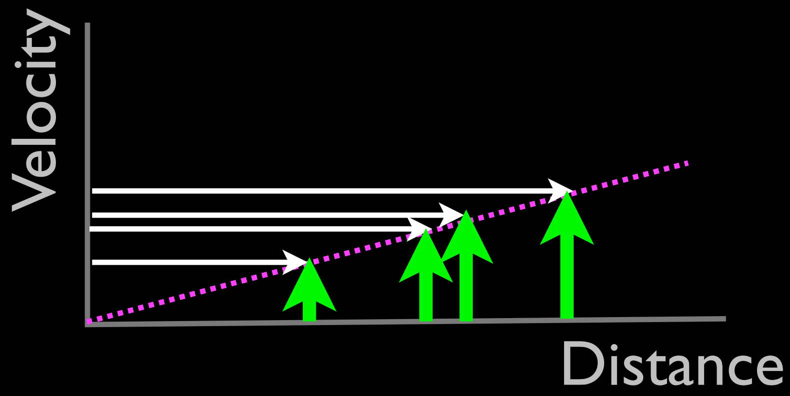
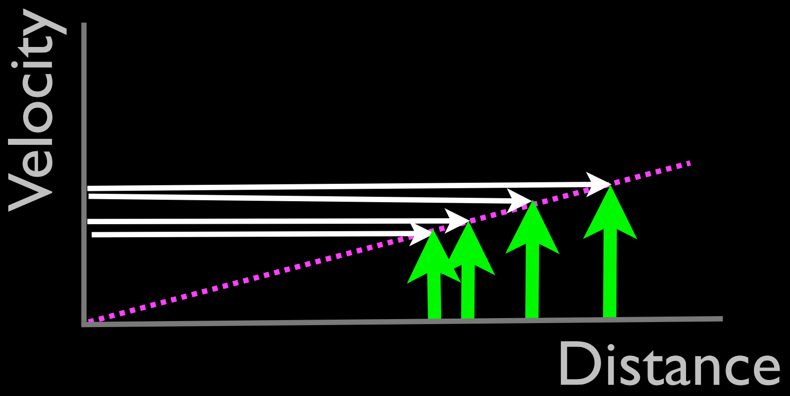




Same Hubble pattern seen from *any* galaxy!





Looks the same in all directions

Looks the same in all directions

Isotropy

Looks the same in all directions

Isotropy

Hubble expansion

$$v = H_0 d$$

Looks the same in
all directions

Isotropy

Hubble
expansion

$$v=H_0\,d$$

⇒

Same pattern seen
from any galaxy

Looks the same in
all directions

Isotropy

Hubble
expansion

$$v = H_0 d$$

⇒

Same pattern seen
from any galaxy

Uniformity

Looks the same in
all directions

Isotropy

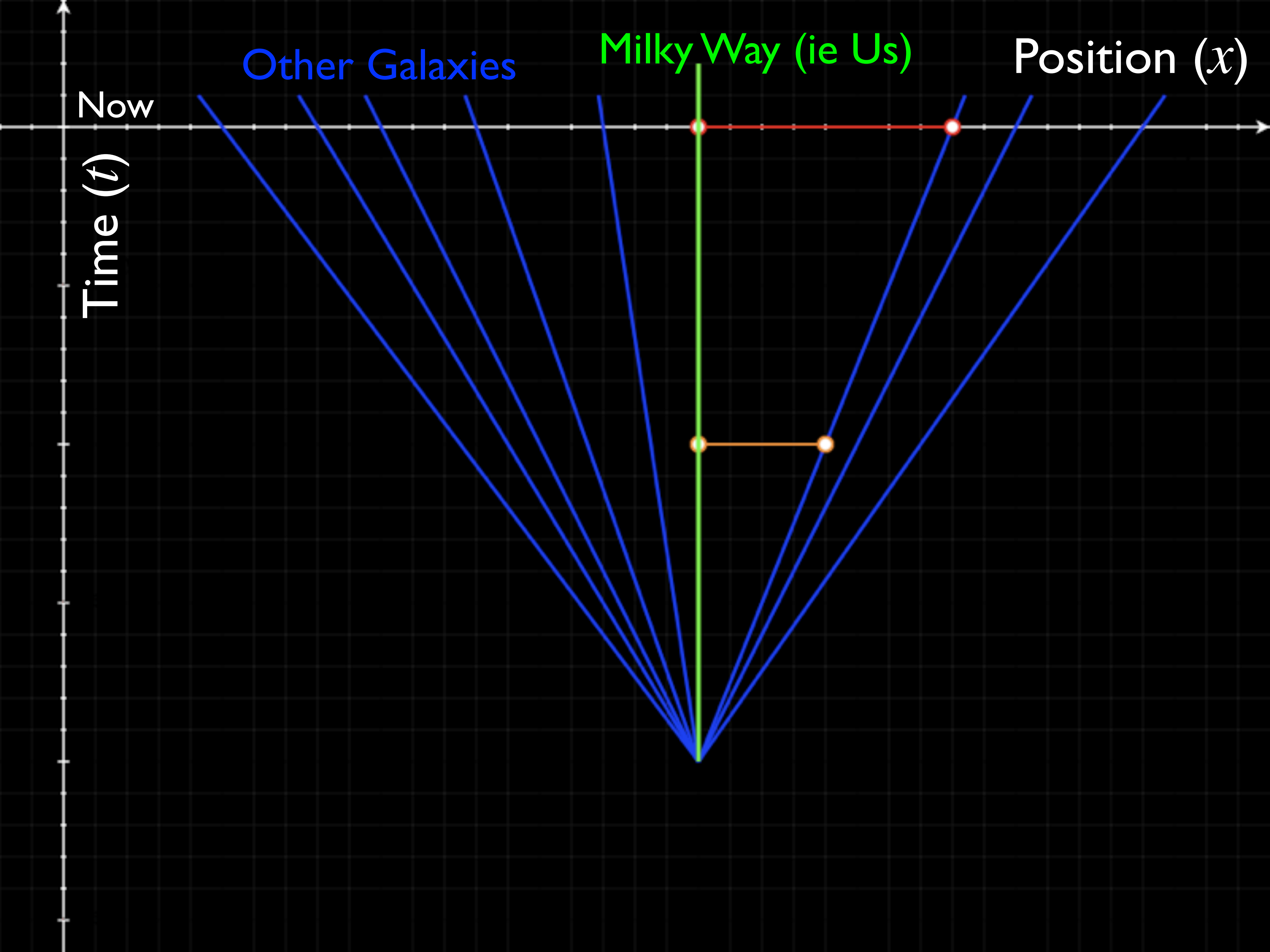
Hubble
expansion

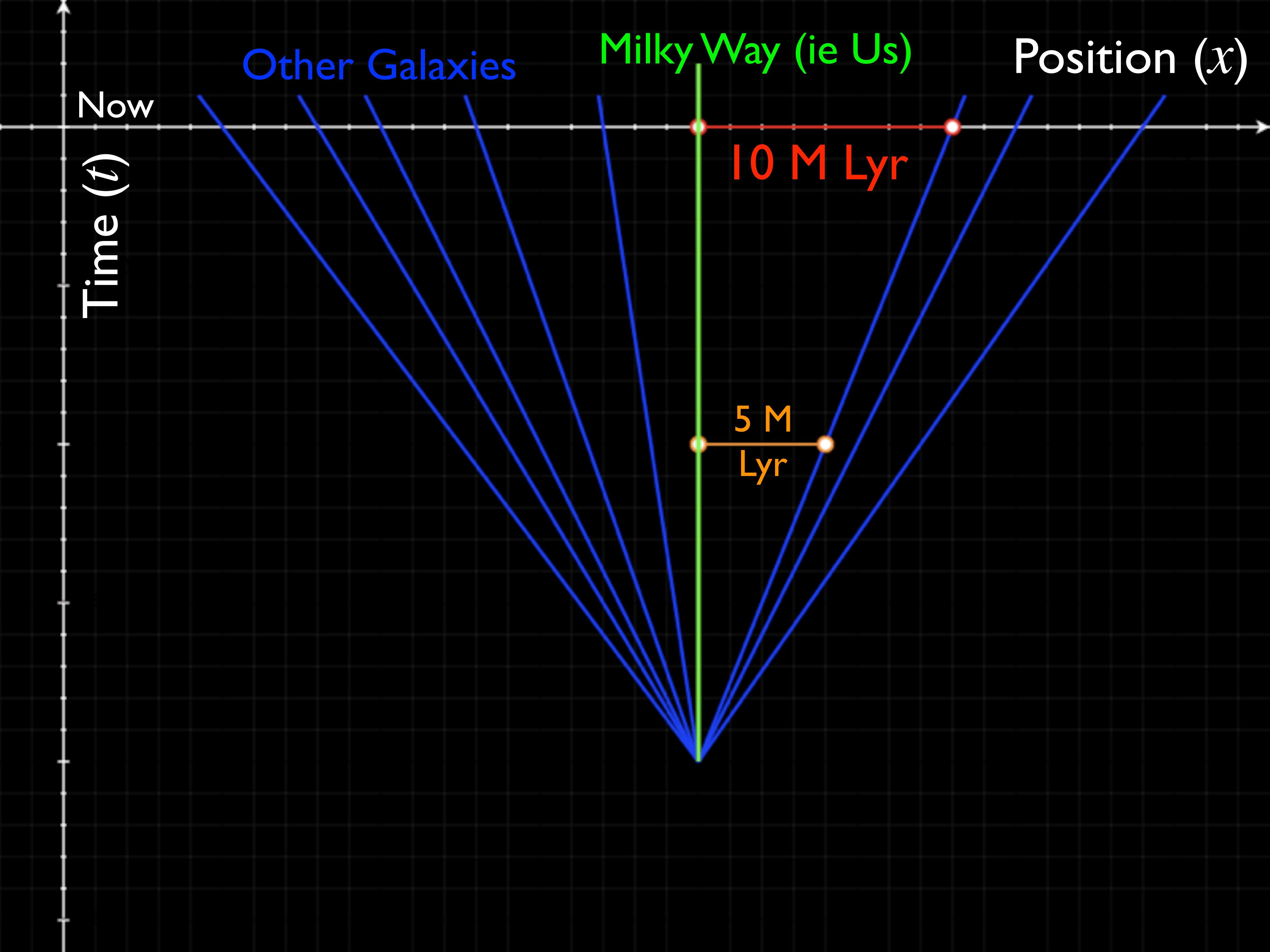
$$v = H_0 \, d$$

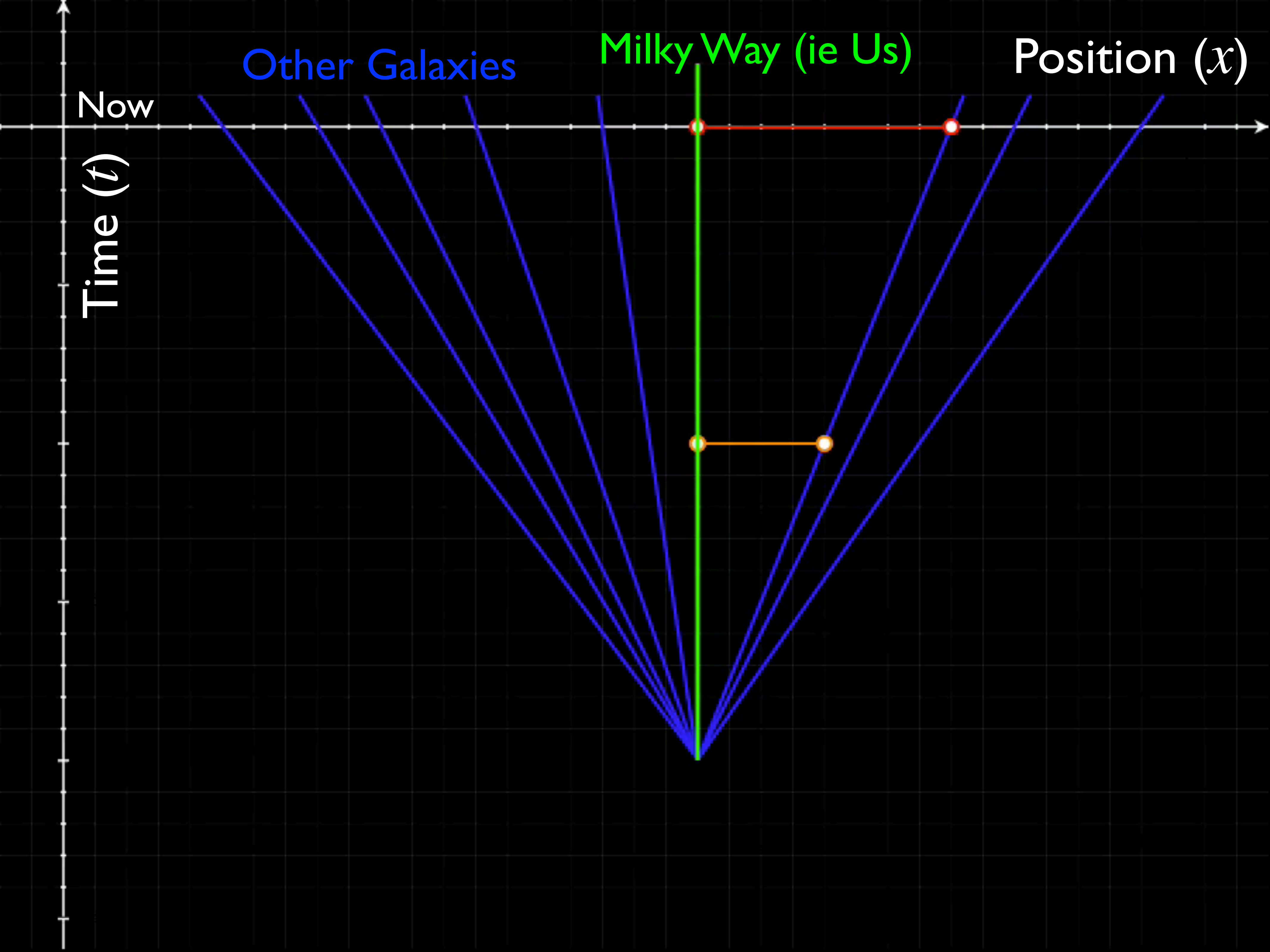
Same pattern seen
from any galaxy

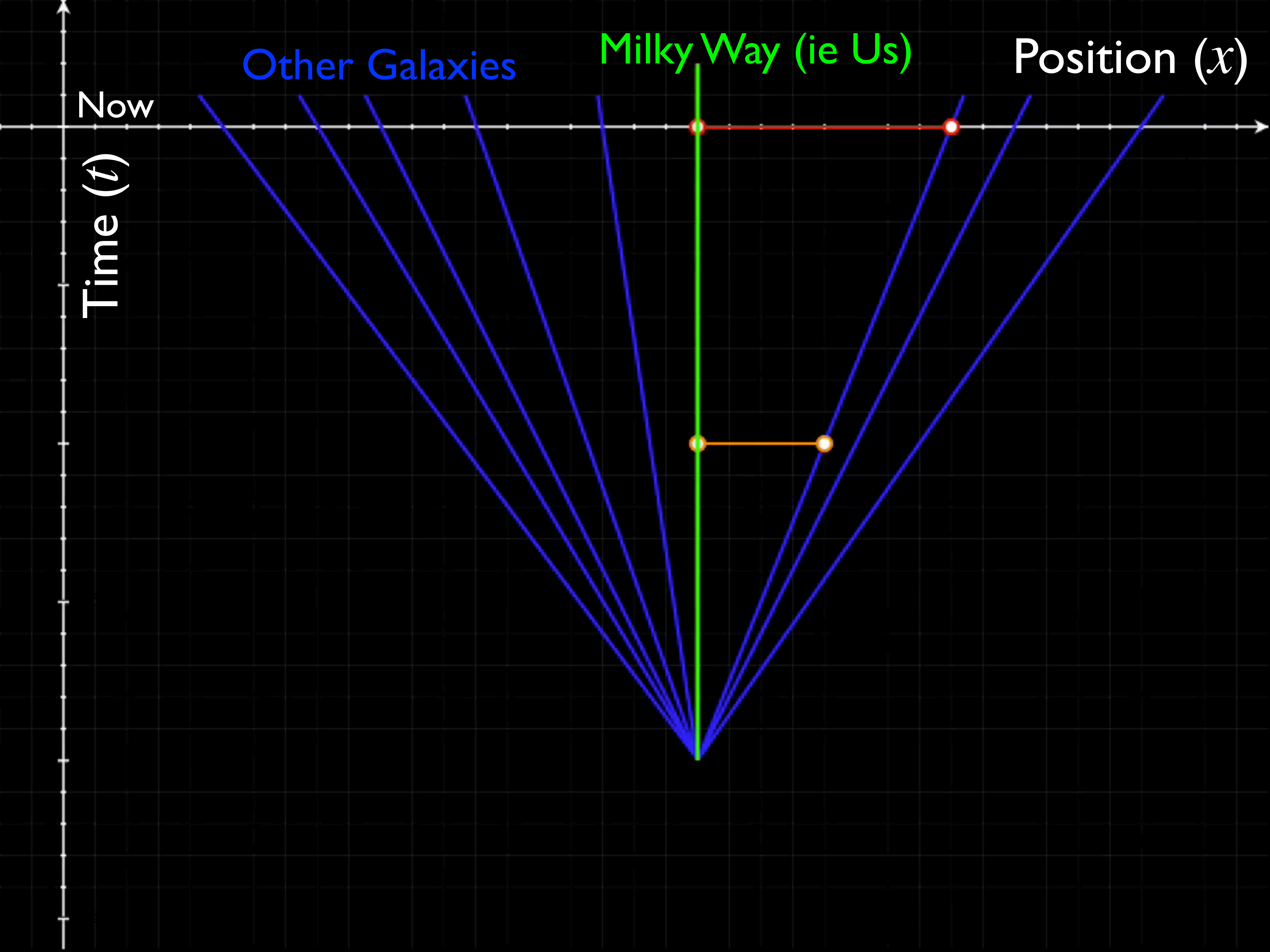
Uniformity

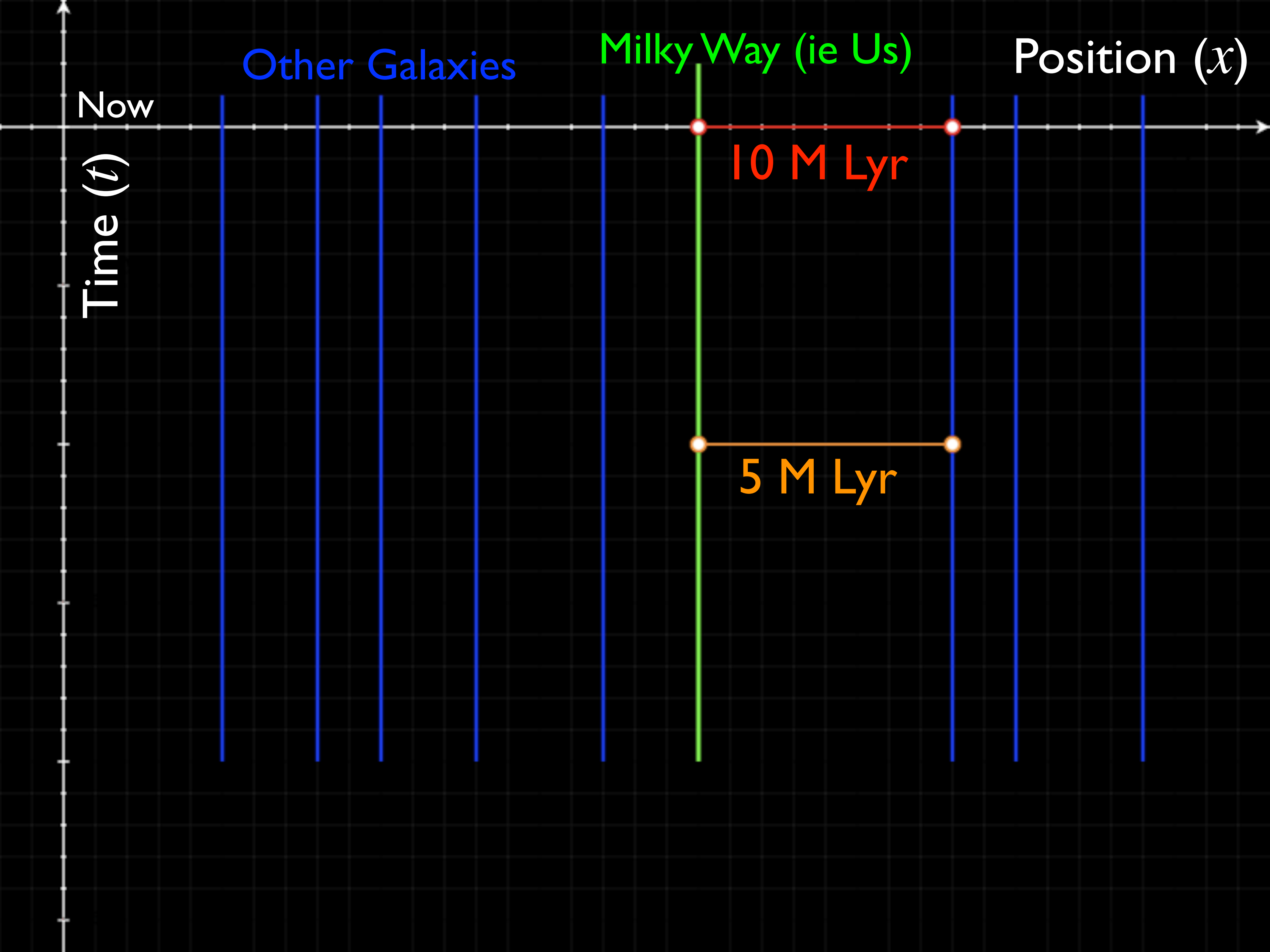
The Universe is (pretty much)
the same everywhere!

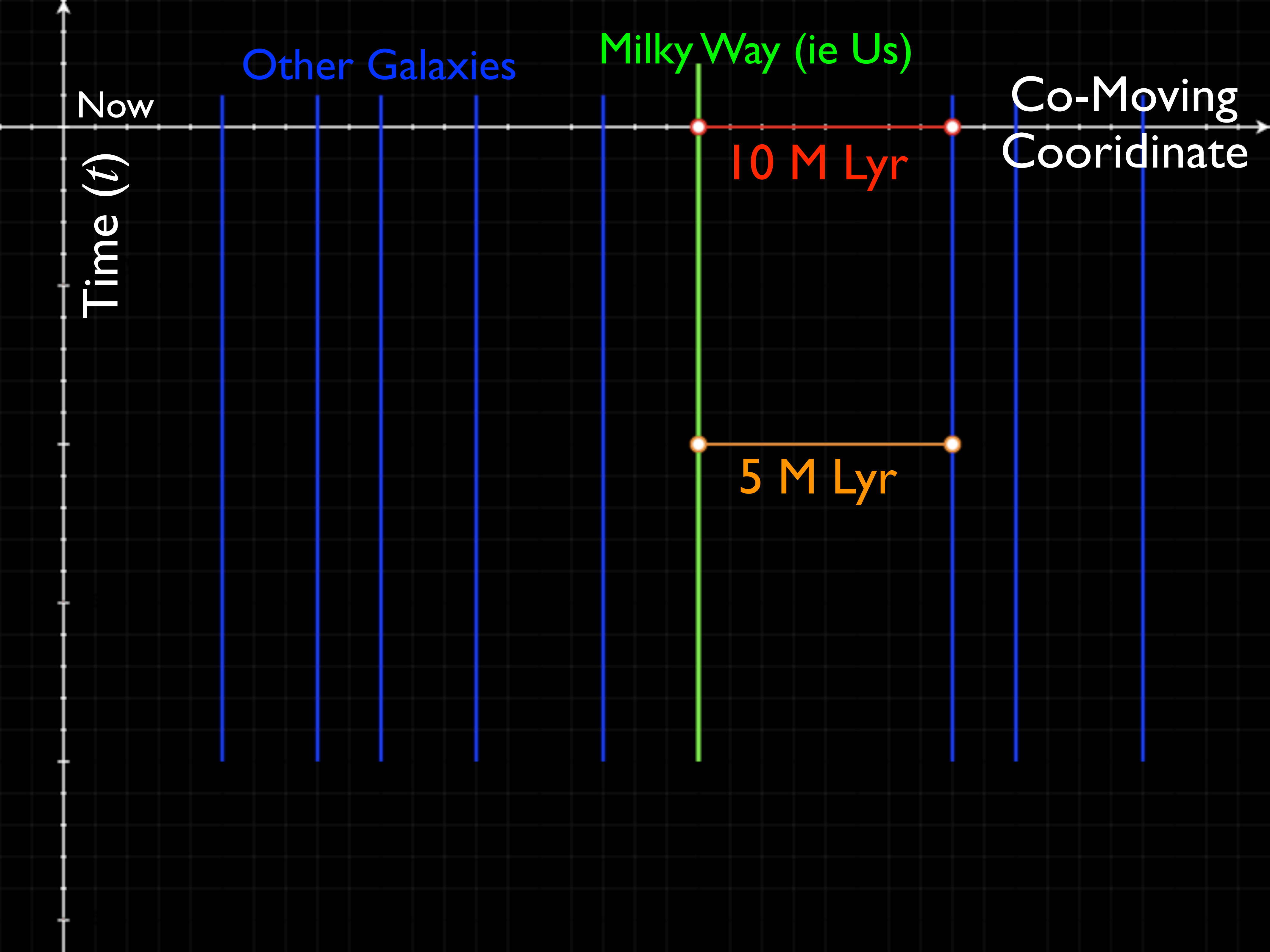

Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)

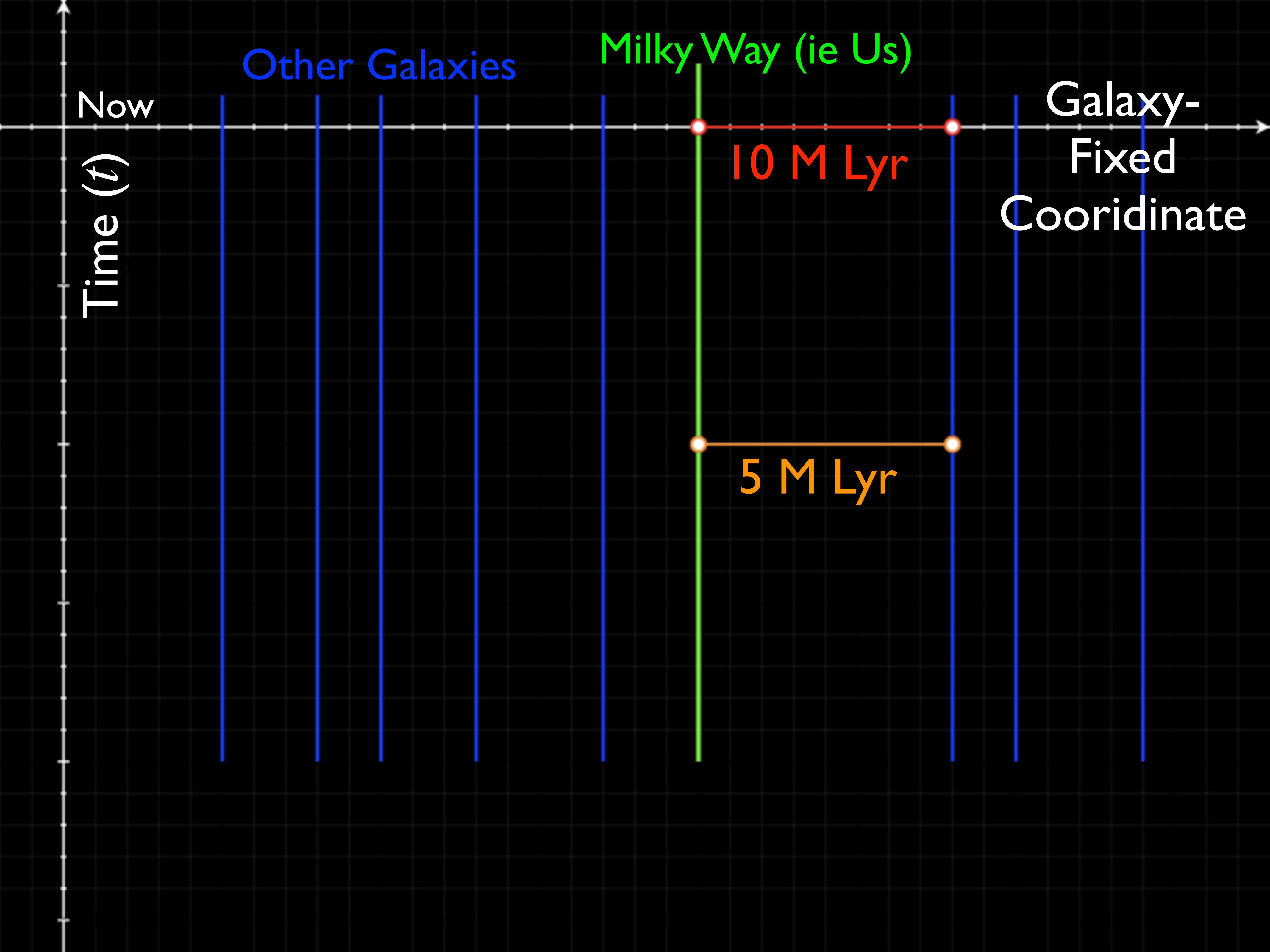

Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)
10 M Lyr
5 M Lyr


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)


Other Galaxies
Milky Way (ie Us)
Position (x)
Now
Time (t)
10 M Lyr
5 M Lyr


Other Galaxies
Milky Way (ie Us)
Now
Co-Moving
Cooridinate
Time (t)
10 M Lyr
5 M Lyr

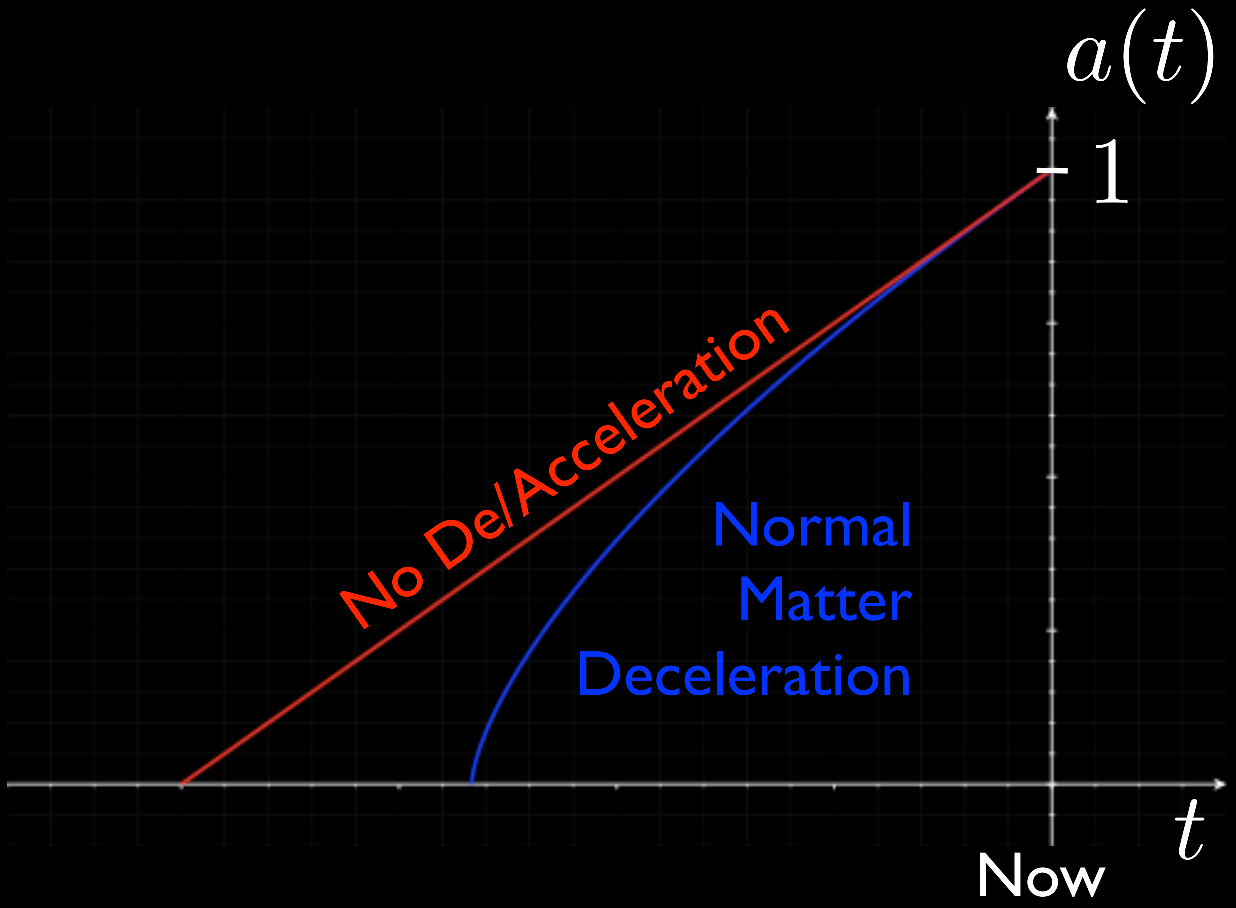

Other Galaxies
Milky Way (ie Us)
Now
Time (t)
10 M Lyr
5 M Lyr
Galaxy-
Fixed
Cooridinate

Universal Scale Factor

$$\boxed{a(t) = \frac{\text{Distance}(t)}{\text{Distance}(\text{Now})}}$$

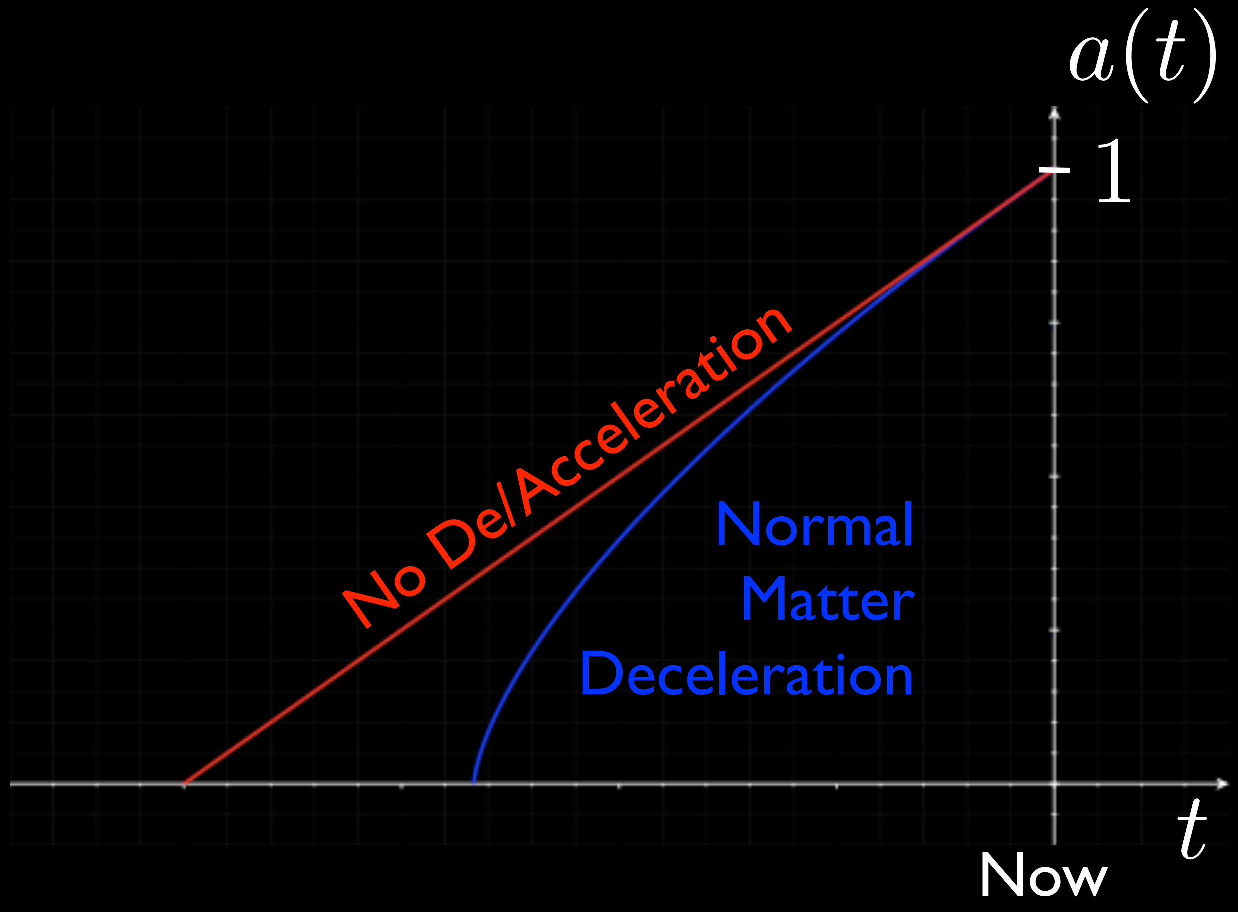
Universal Scale Factor

$$\boxed{a(t) = \frac{\text{Distance}(t)}{\text{Distance}(\text{Now})}}$$



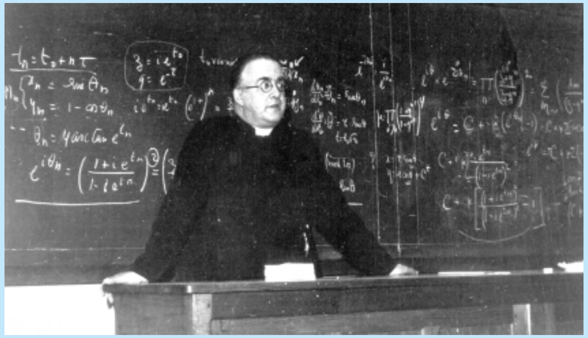
Universal Scale Factor

$$\boxed{a(t) = \frac{\text{Distance}(t)}{\text{Distance}(\text{Now})}}$$



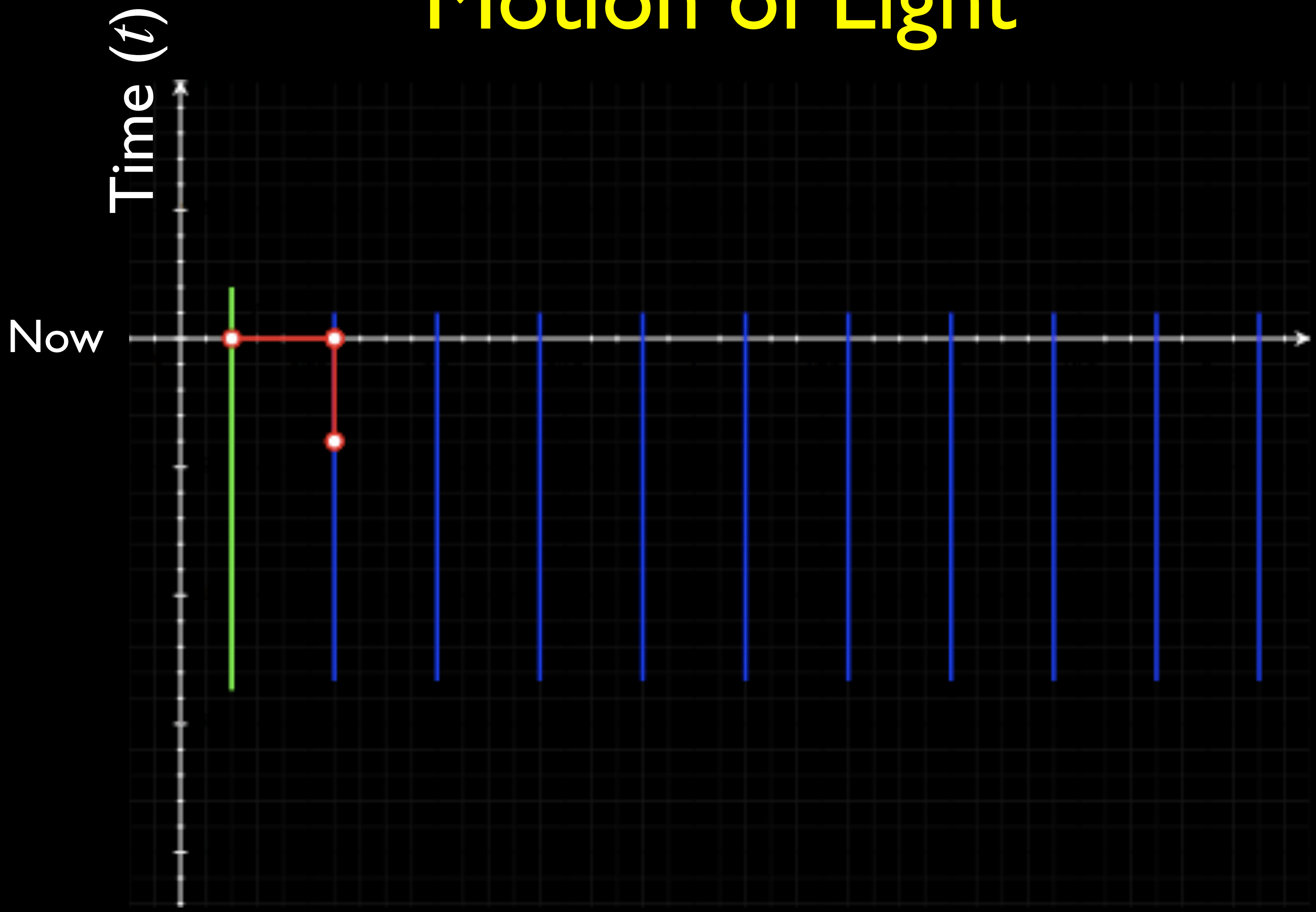
A. Friedmann
Russian

G. LeMaitre
Belgian

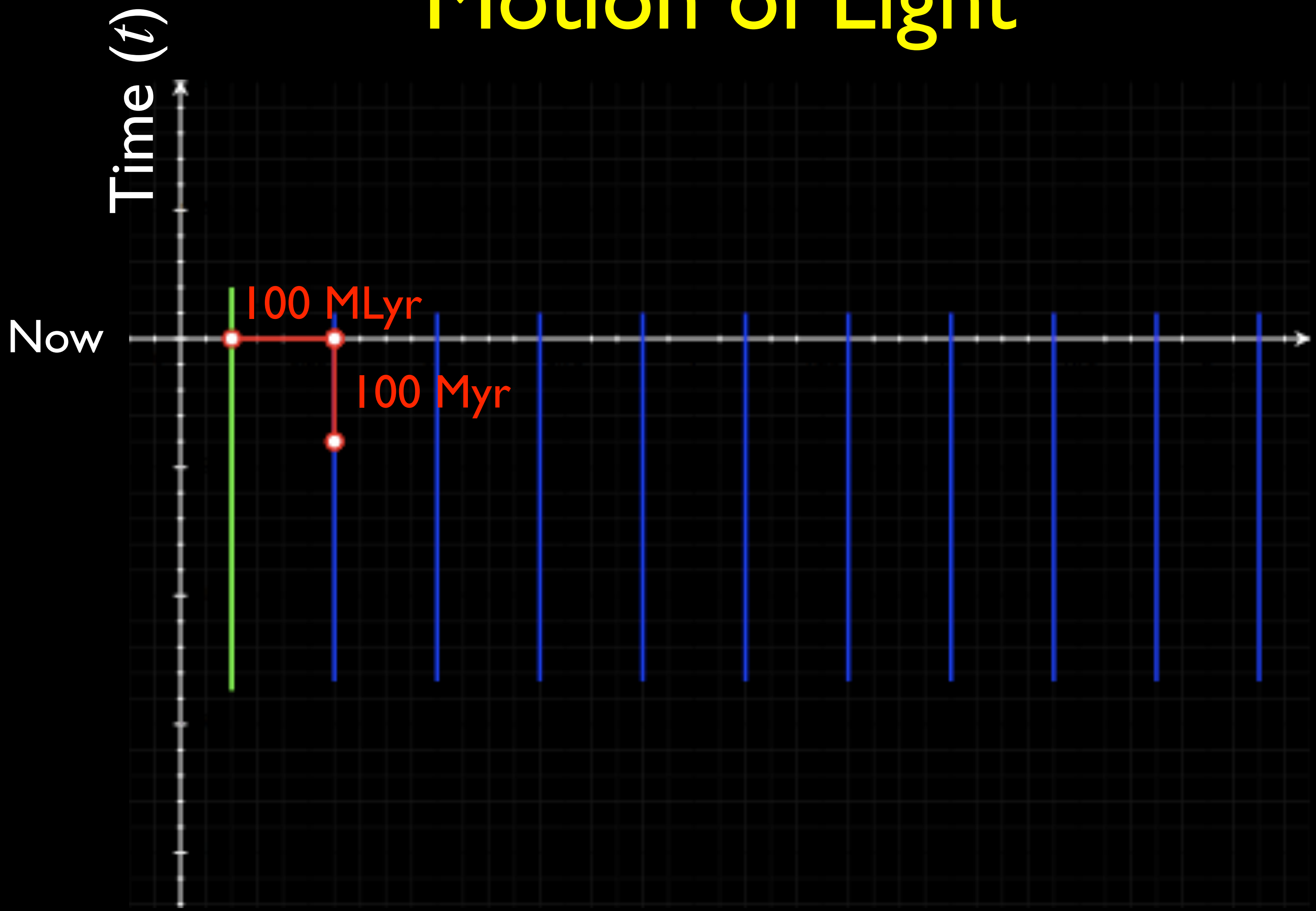


Evolution of homogeneous, non-static (expanding) universes
"Friedmann models" (1922, 1927)

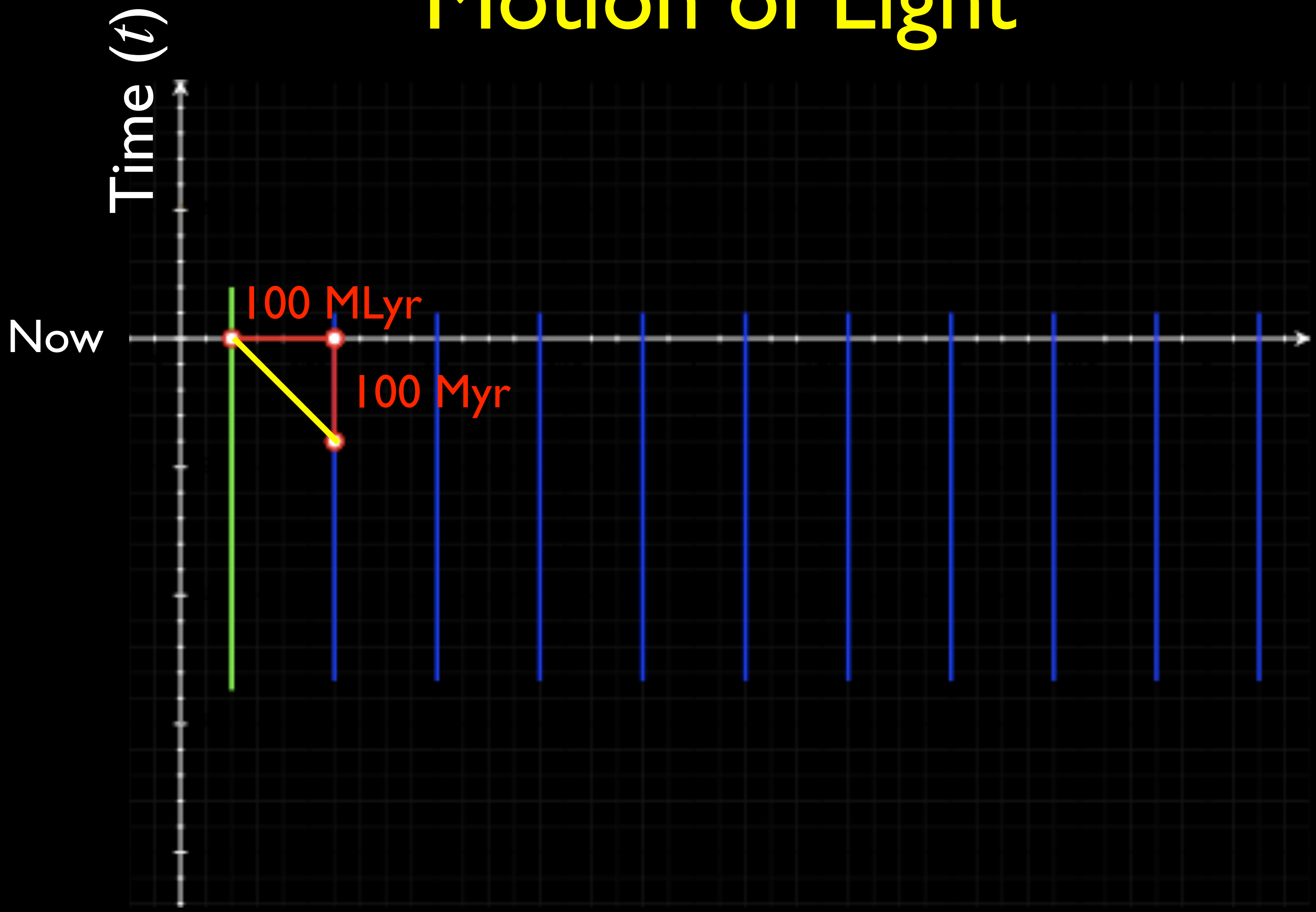
Motion of Light



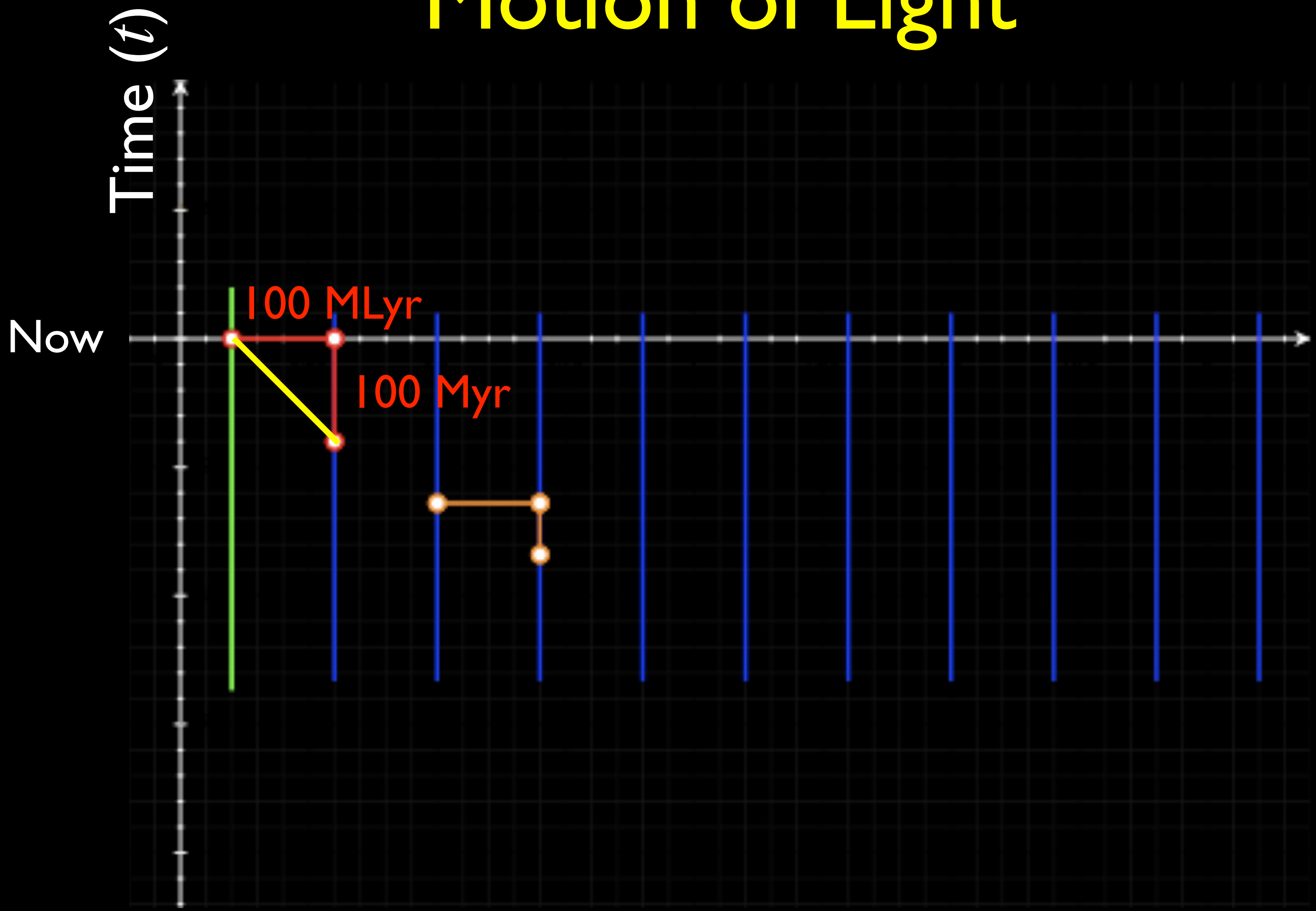
Motion of Light



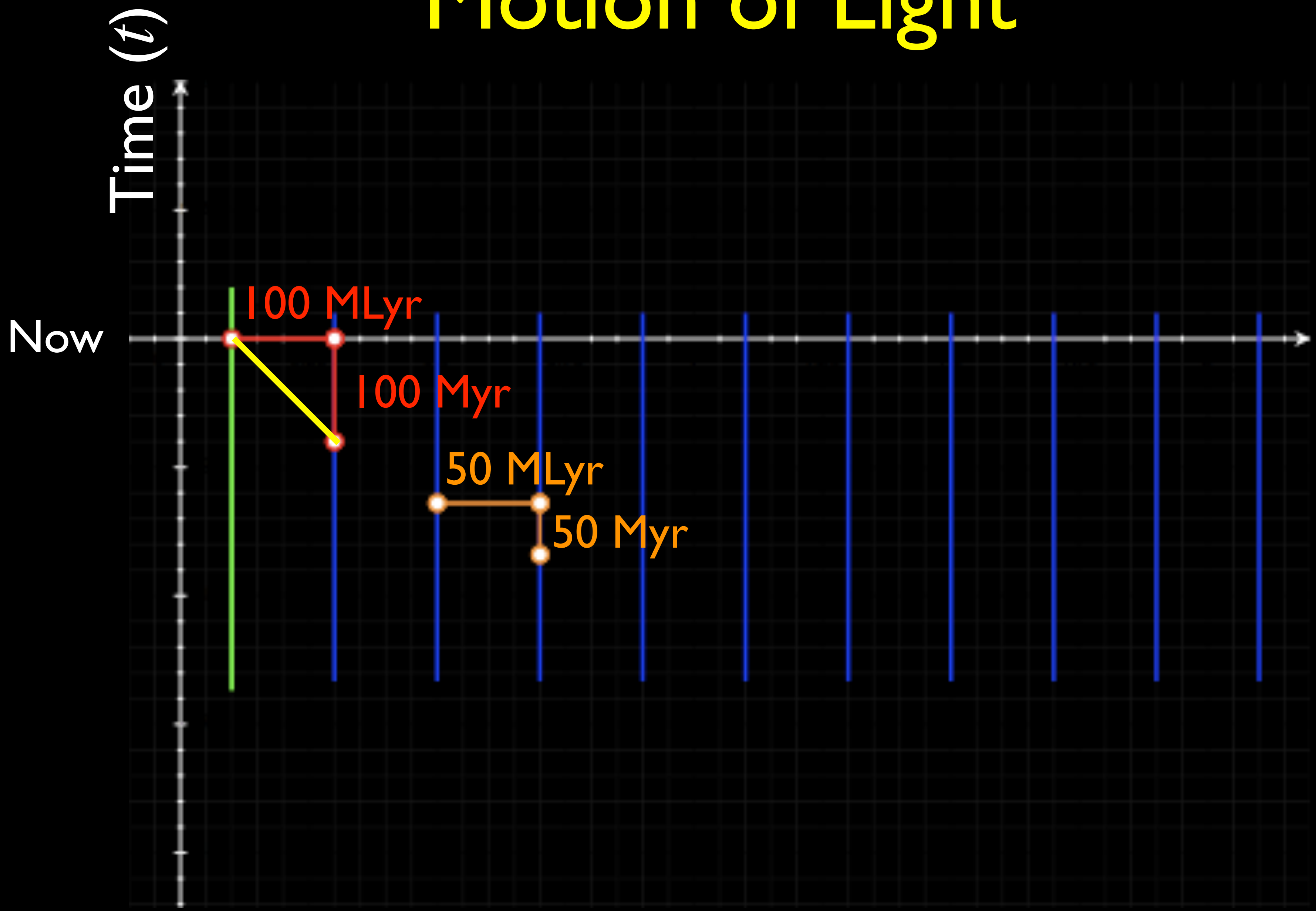
Motion of Light



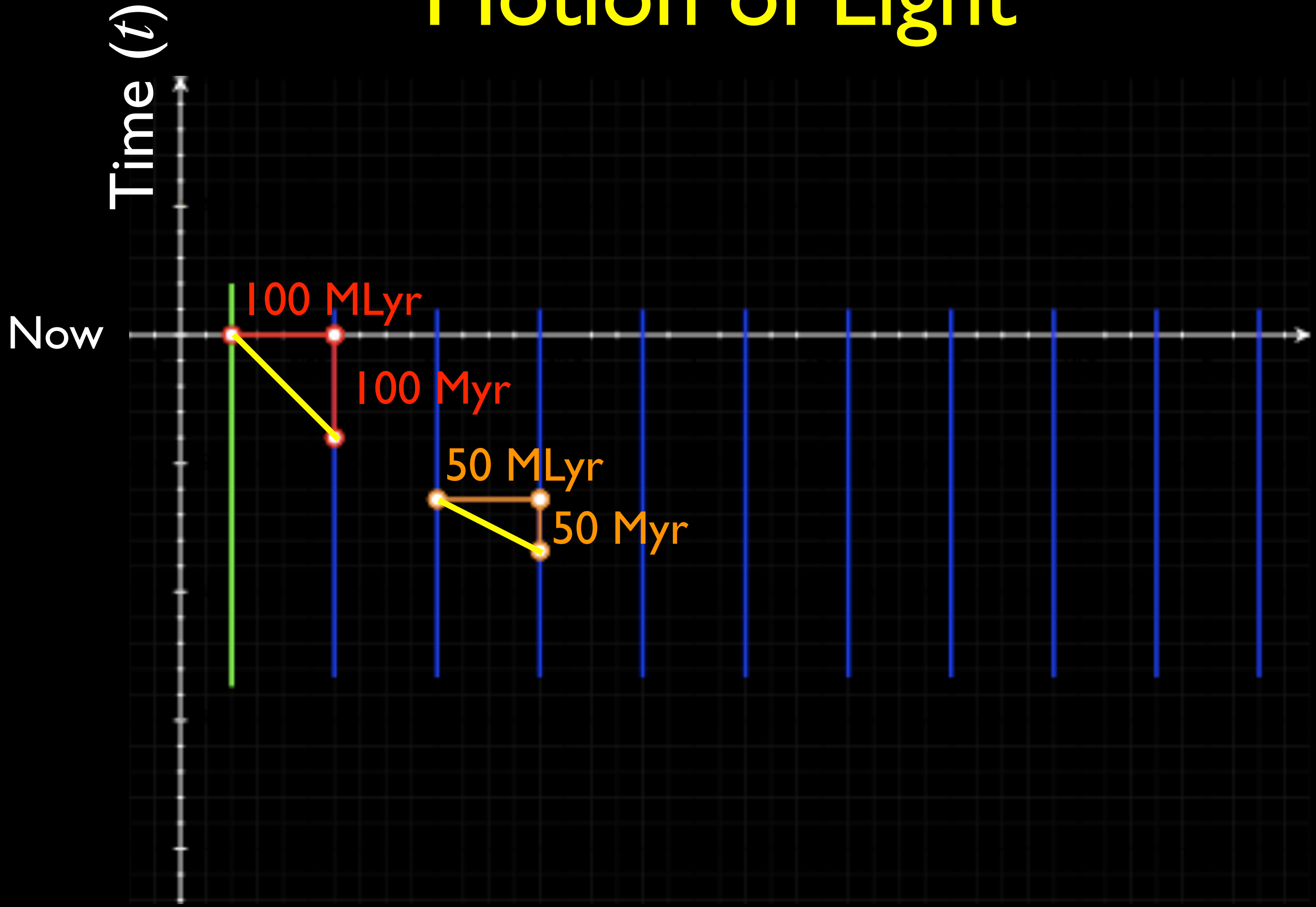
Motion of Light



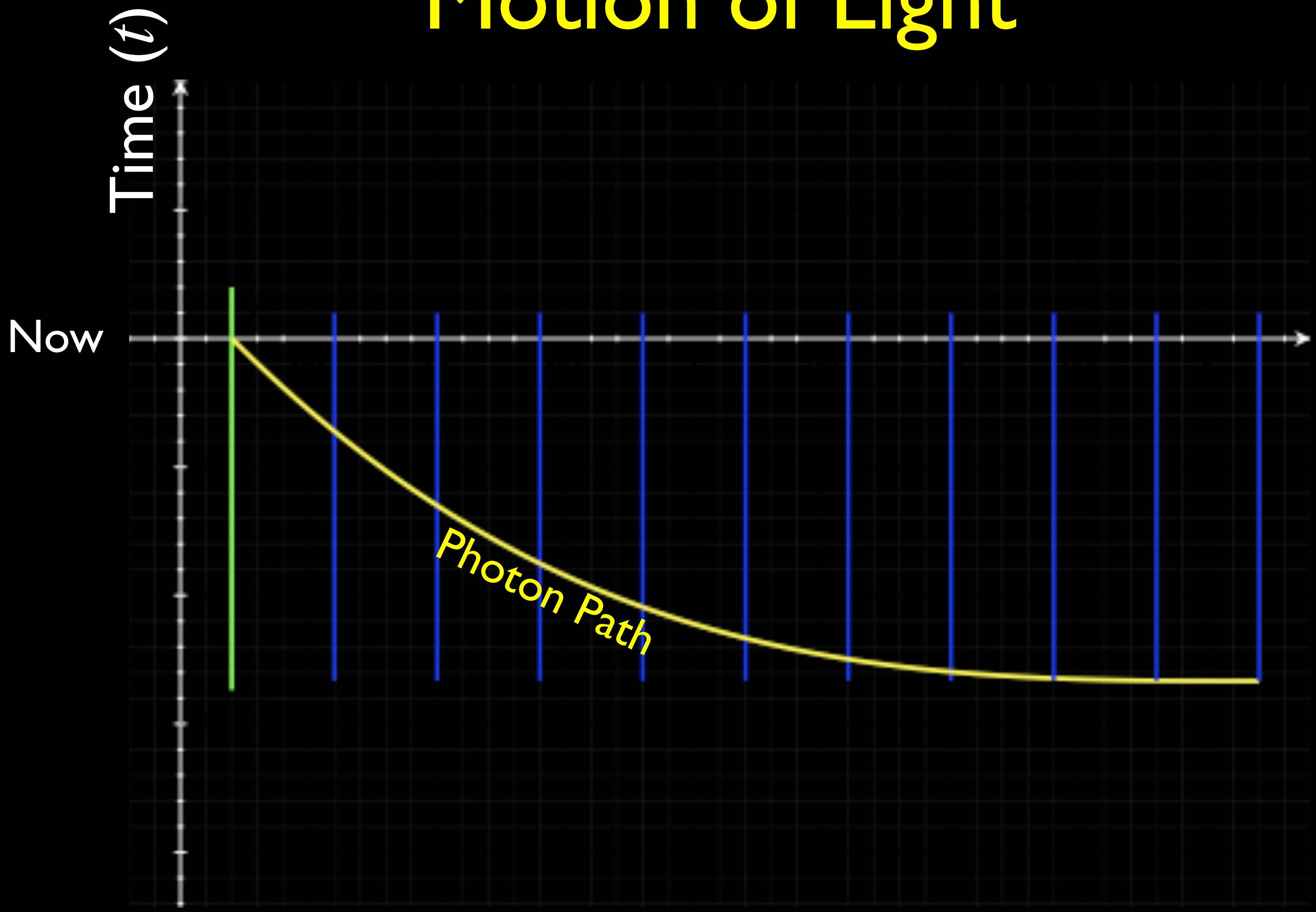
Motion of Light



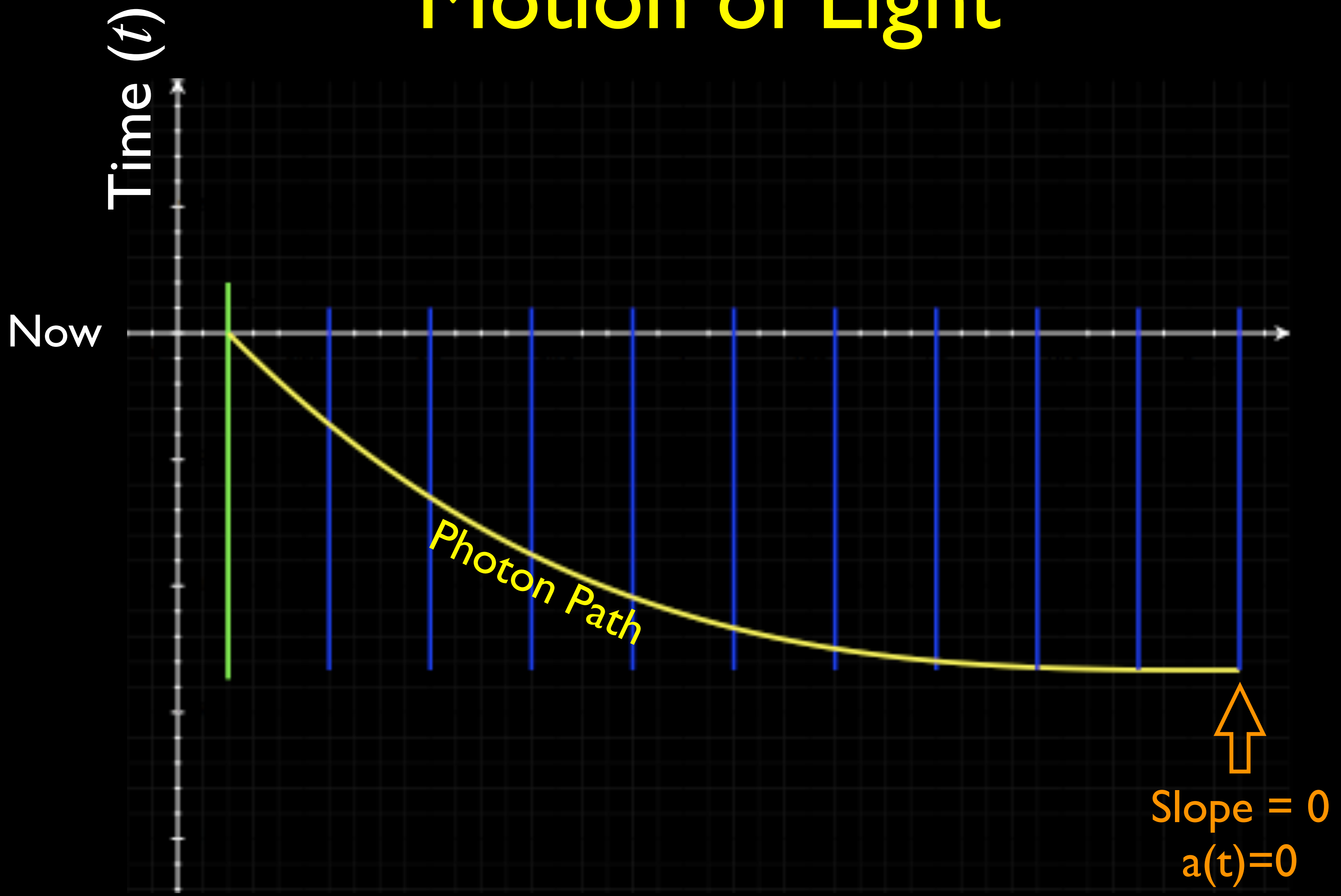
Motion of Light



Motion of Light

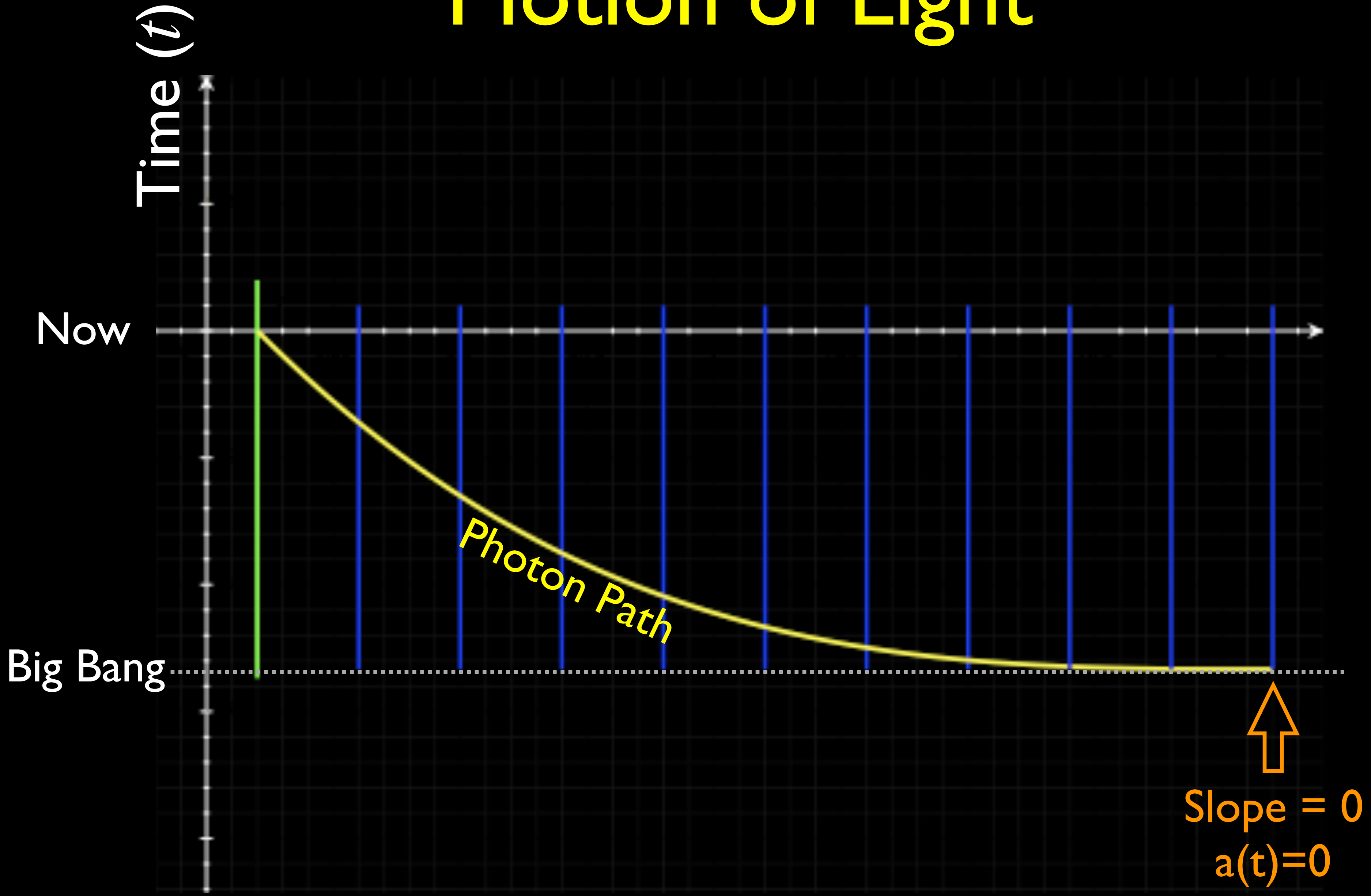


Motion of Light

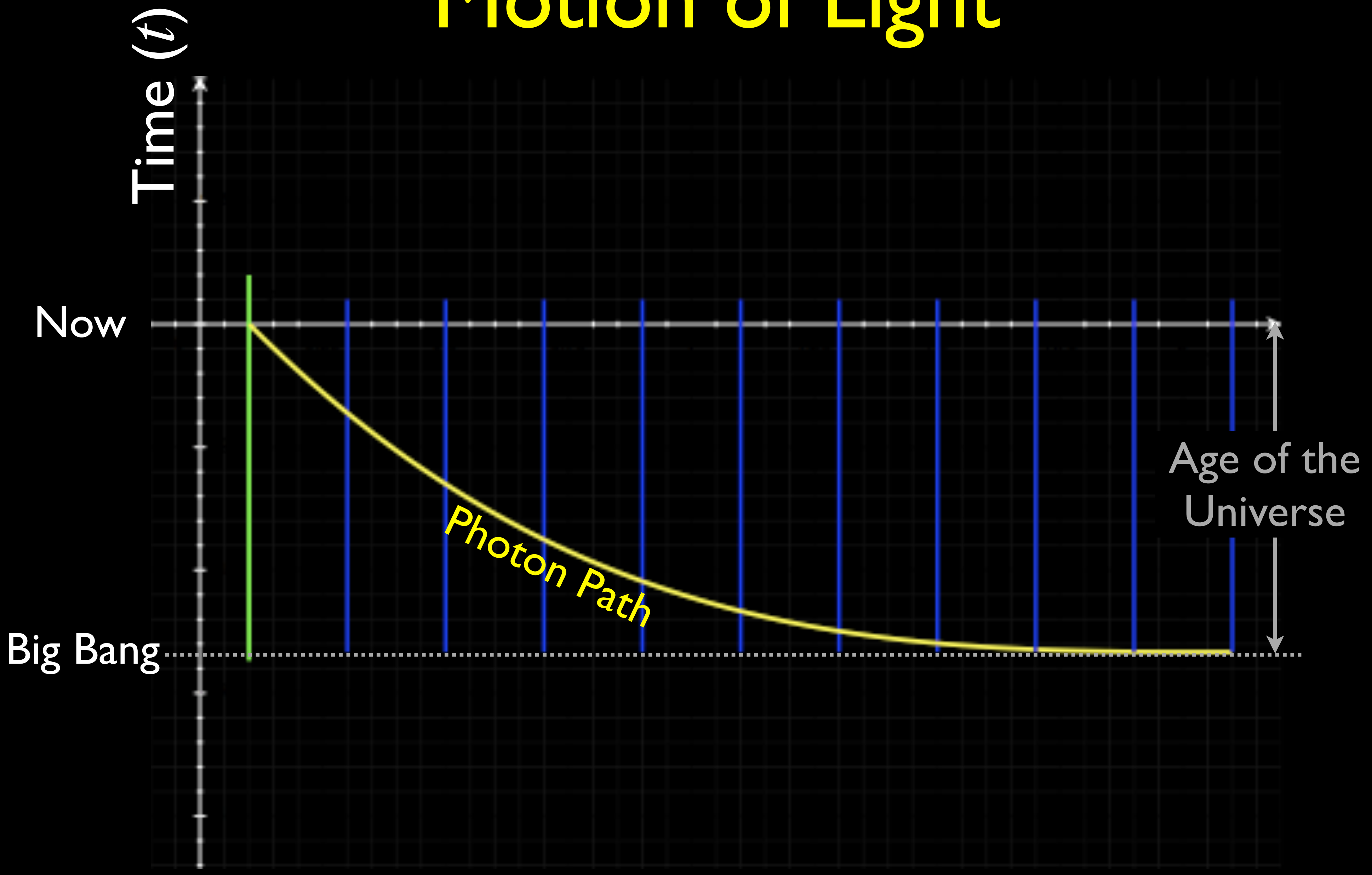


Slope = 0
a(t)=0

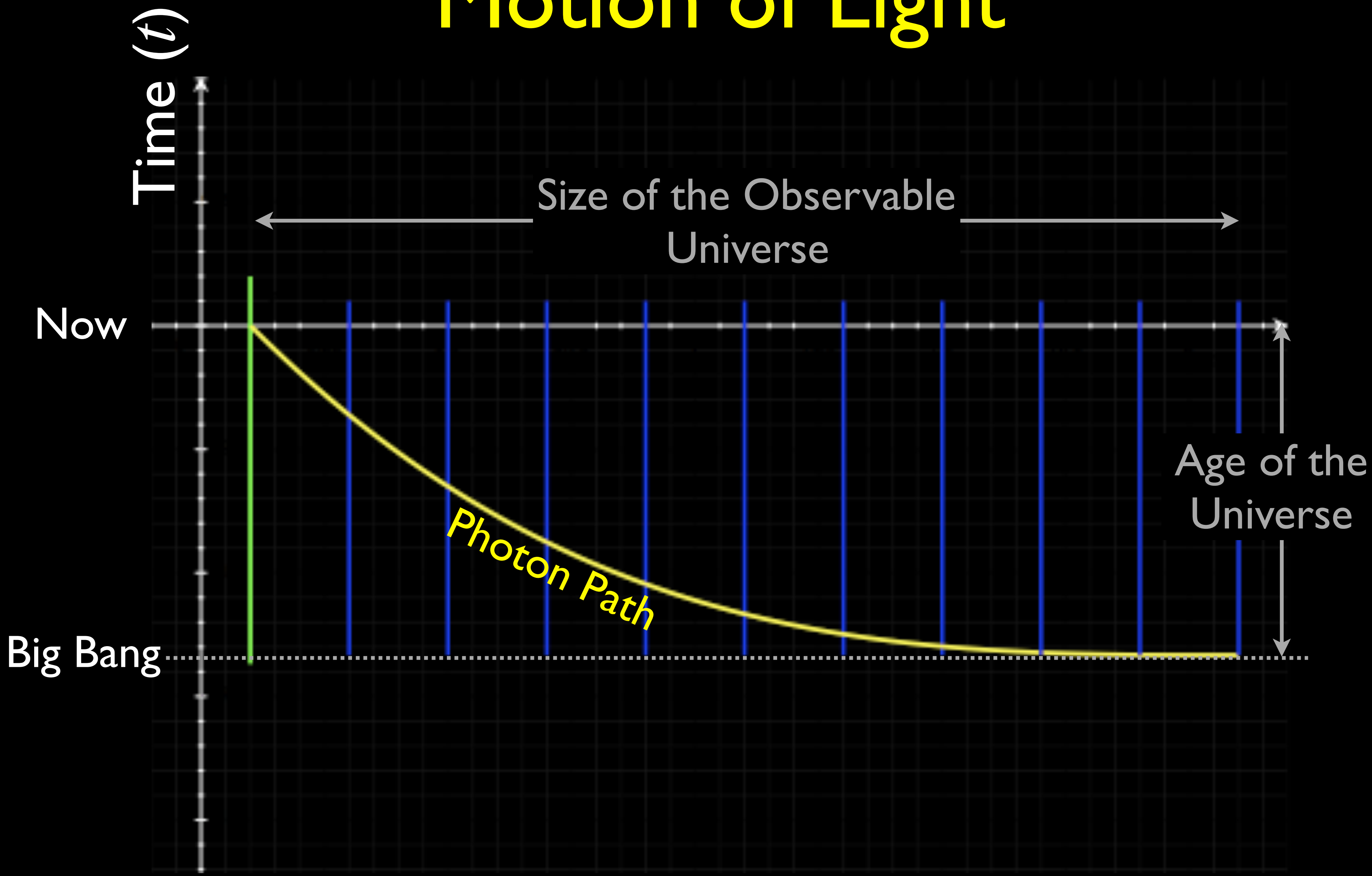
Motion of Light



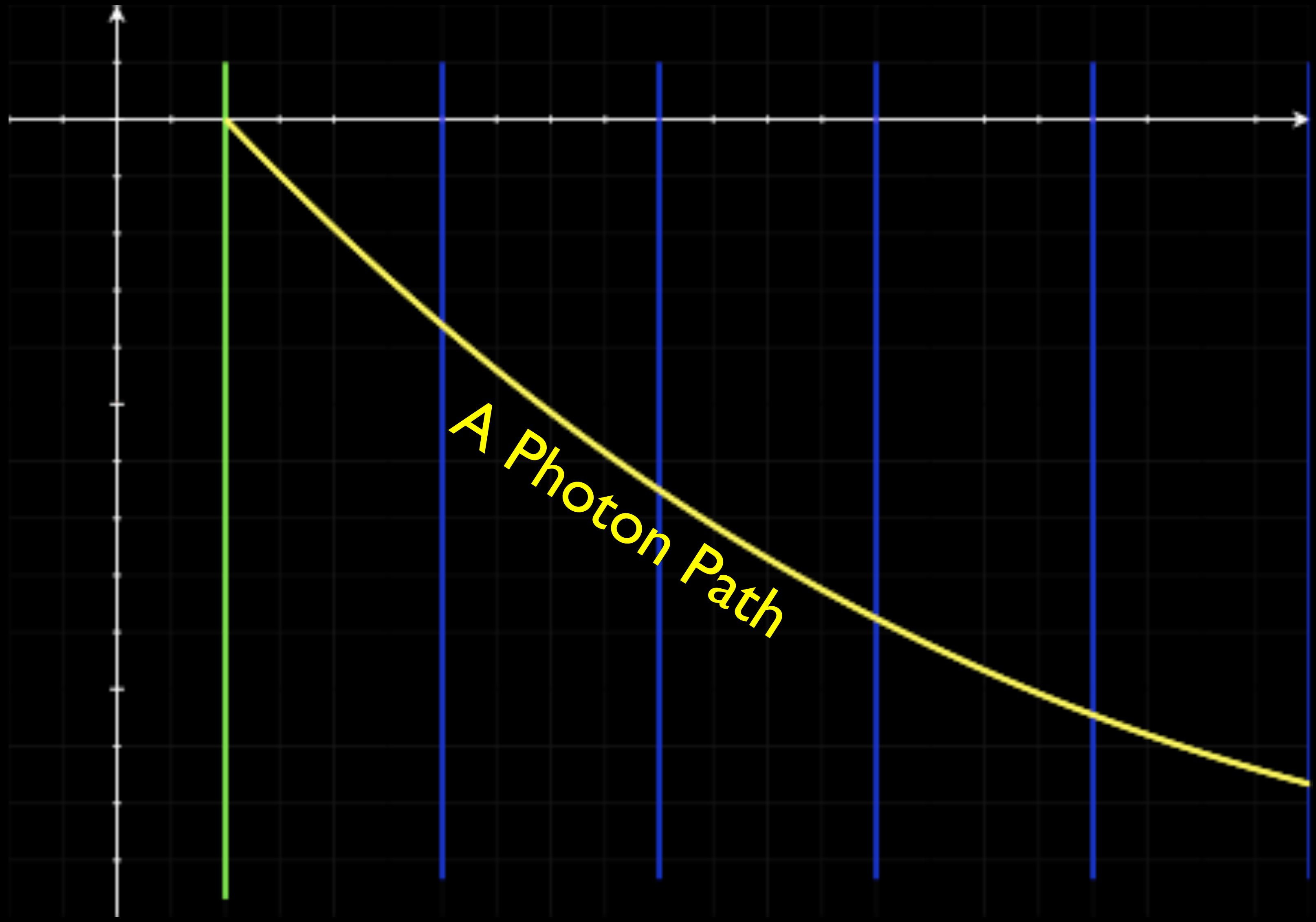
Motion of Light



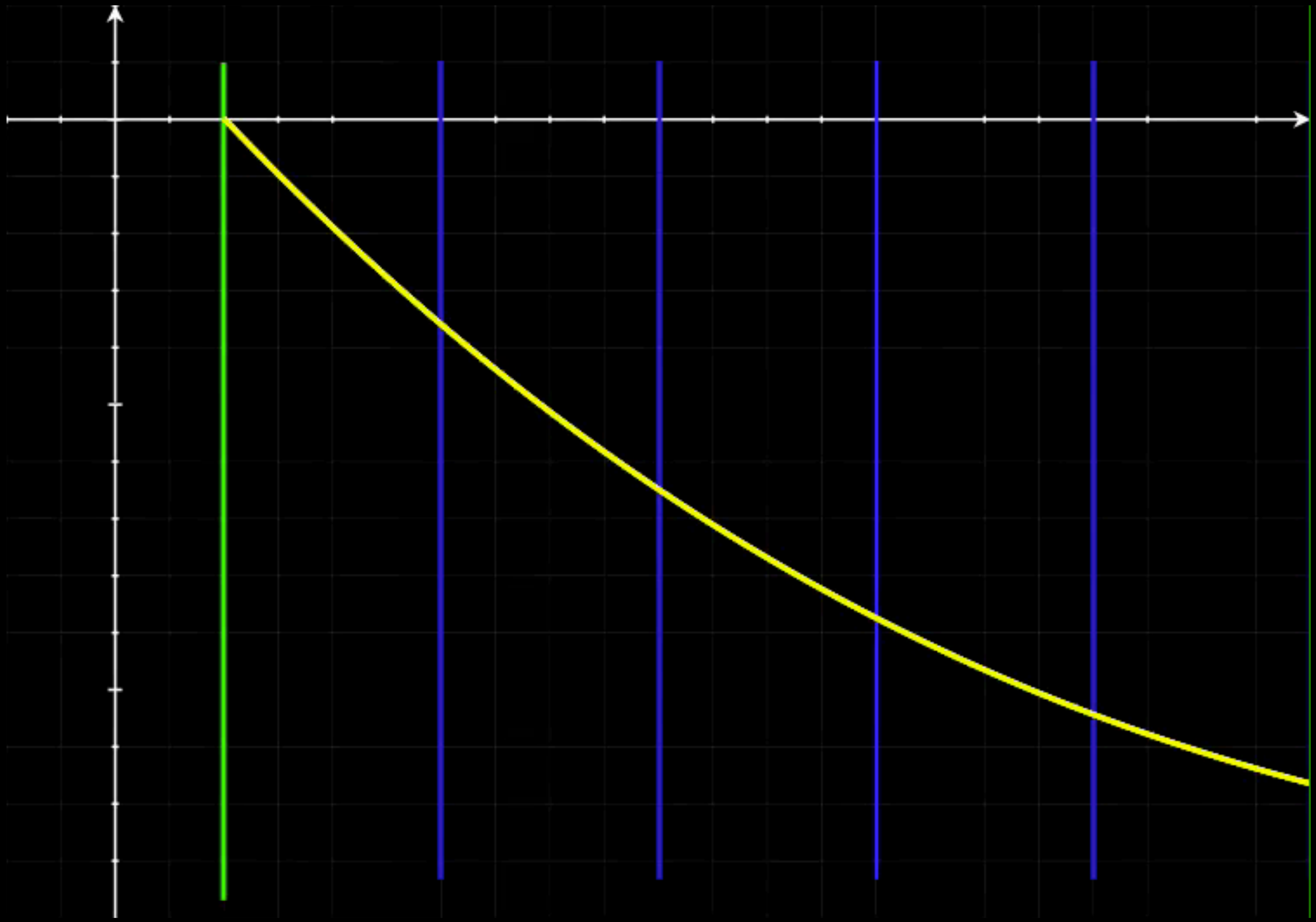
Motion of Light



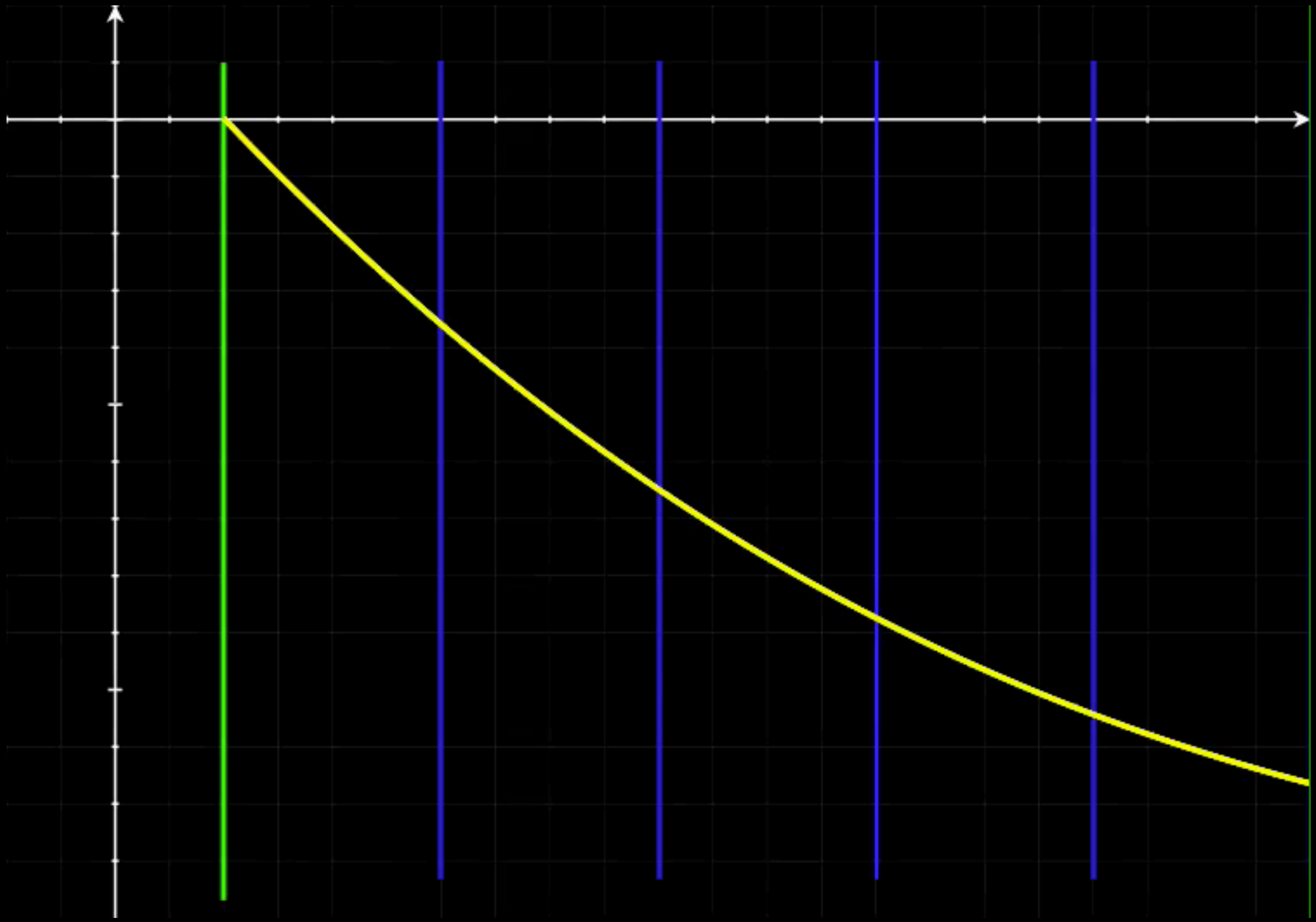
Cosmological Red Shift



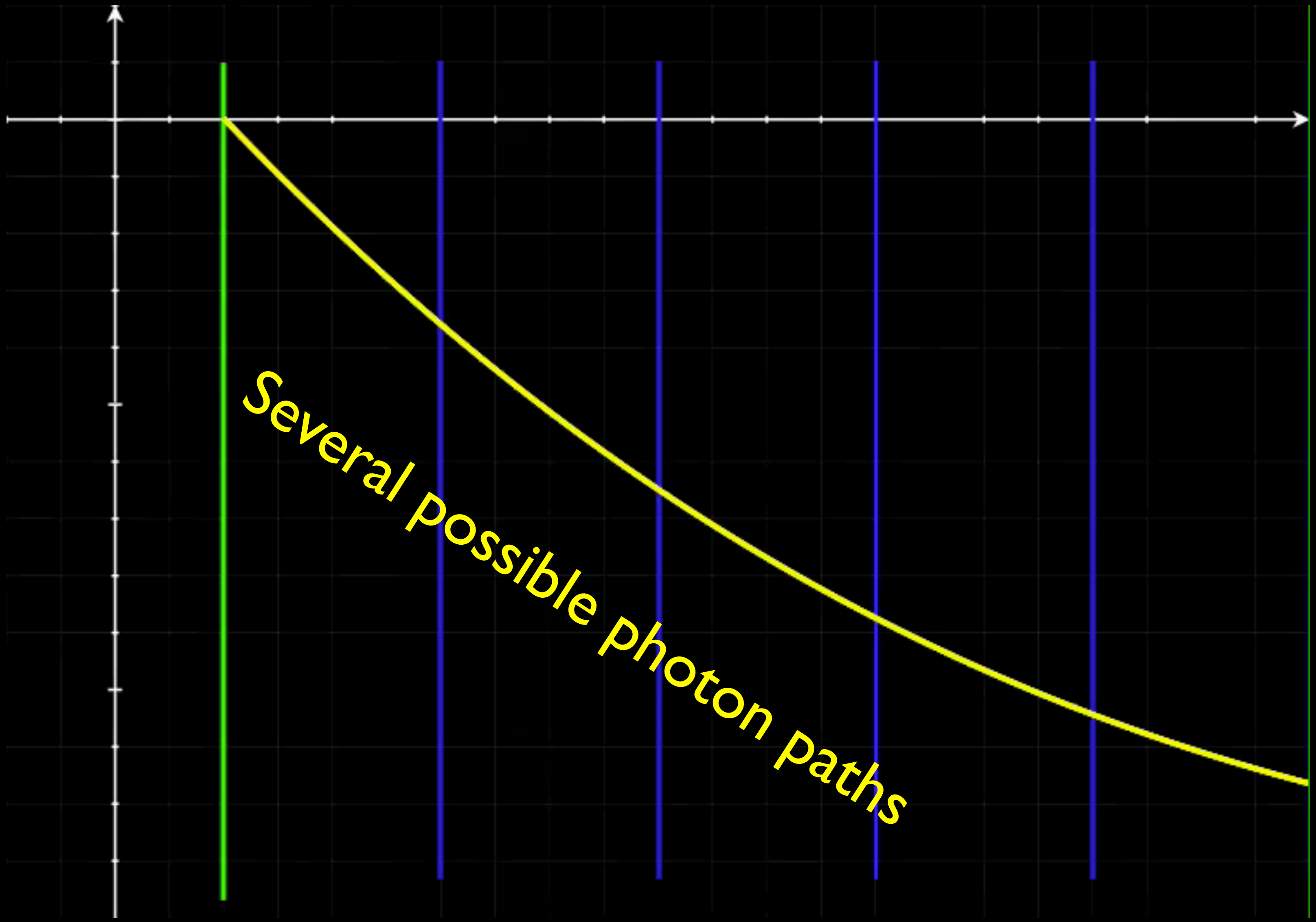
Cosmological Red Shift



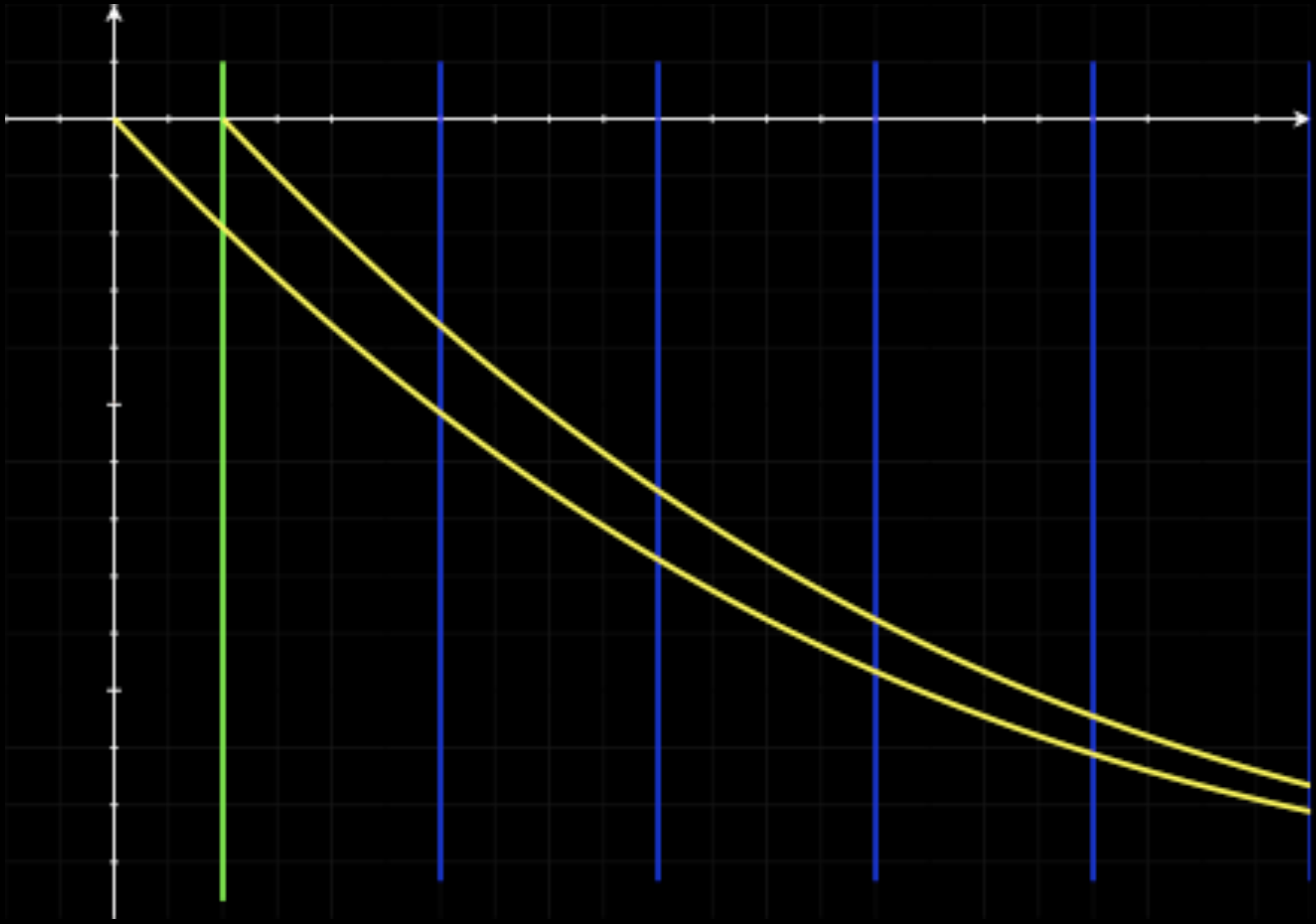
Cosmological Red Shift



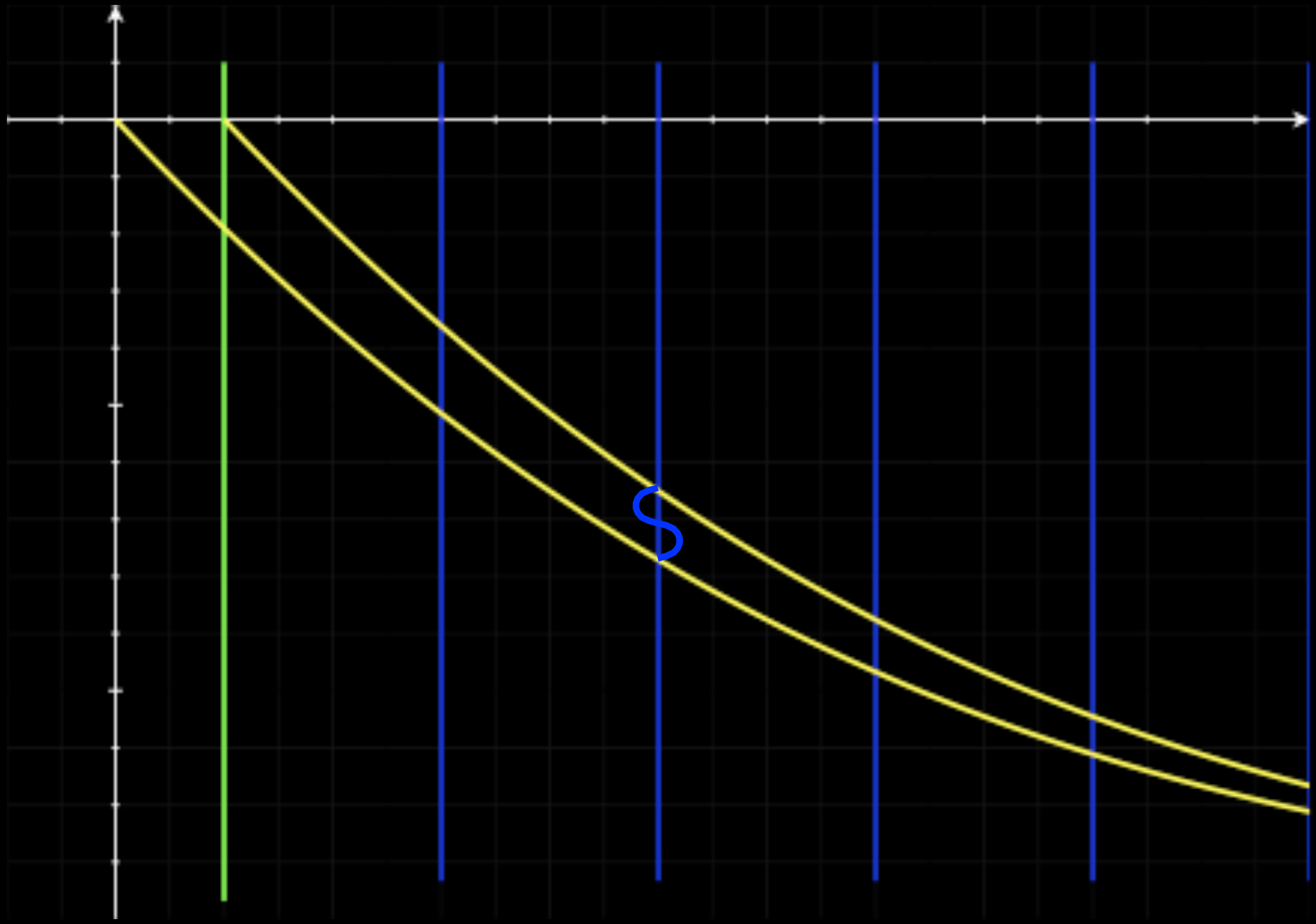
Cosmological Red Shift



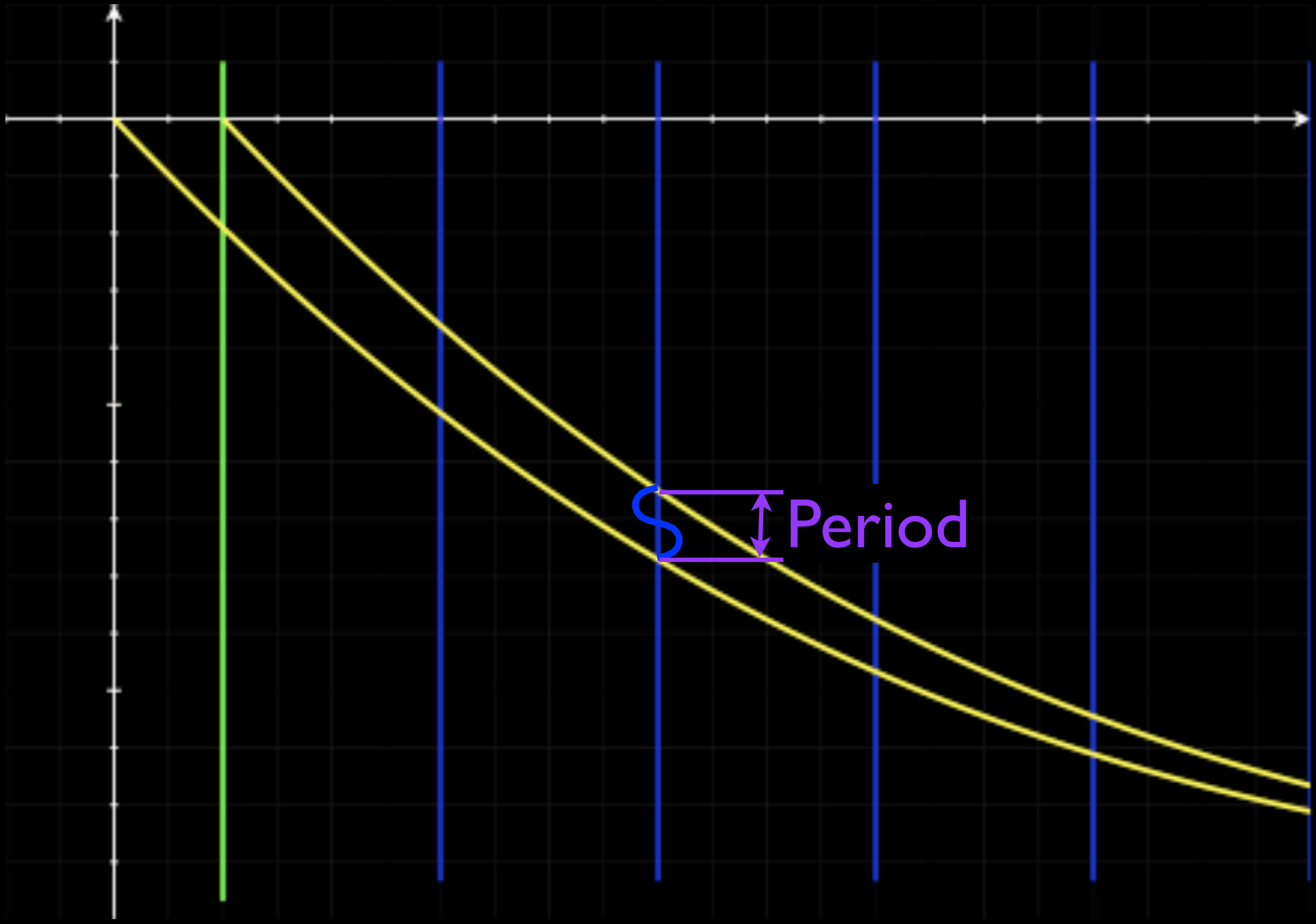
Cosmological Red Shift



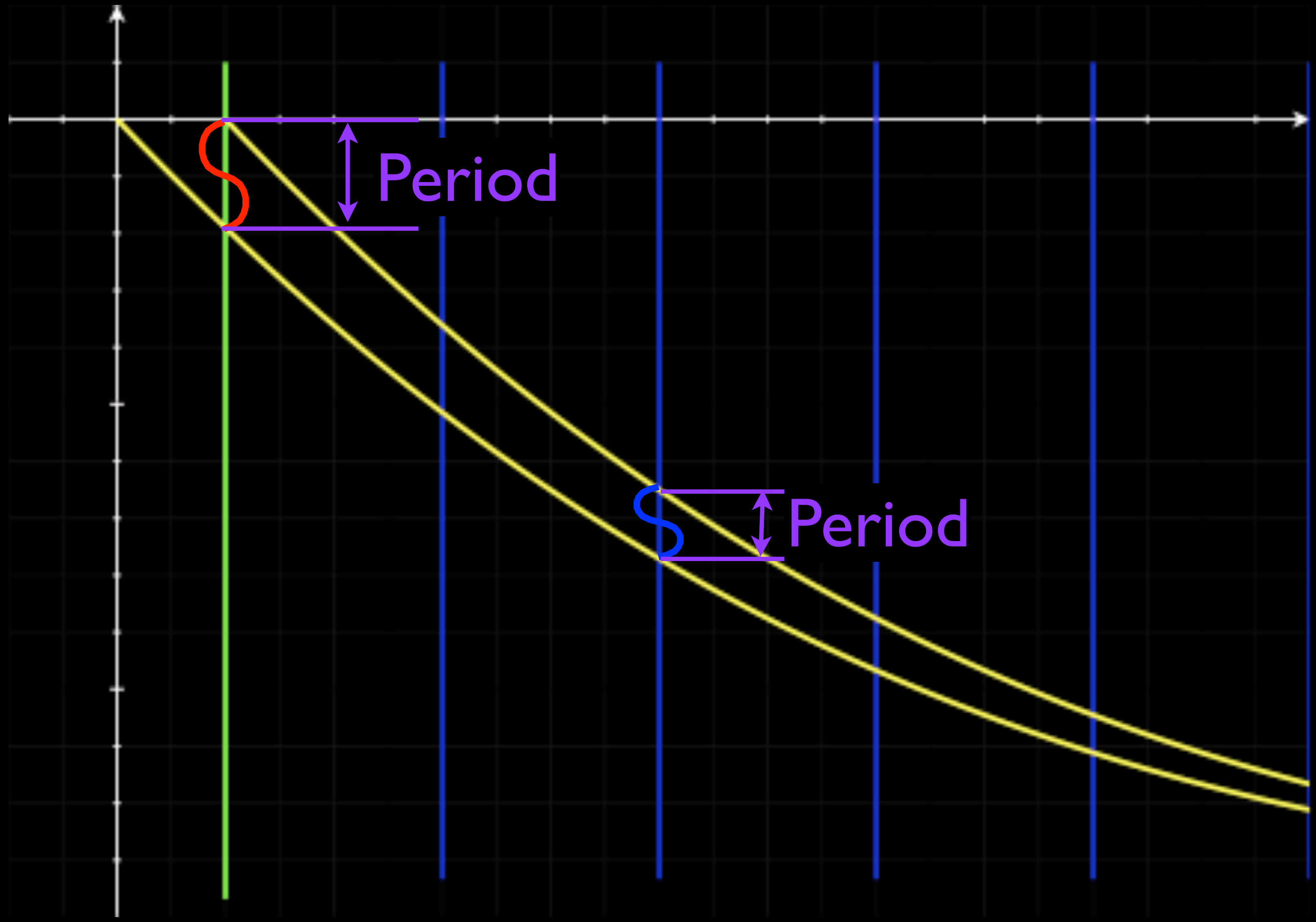
Cosmological Red Shift



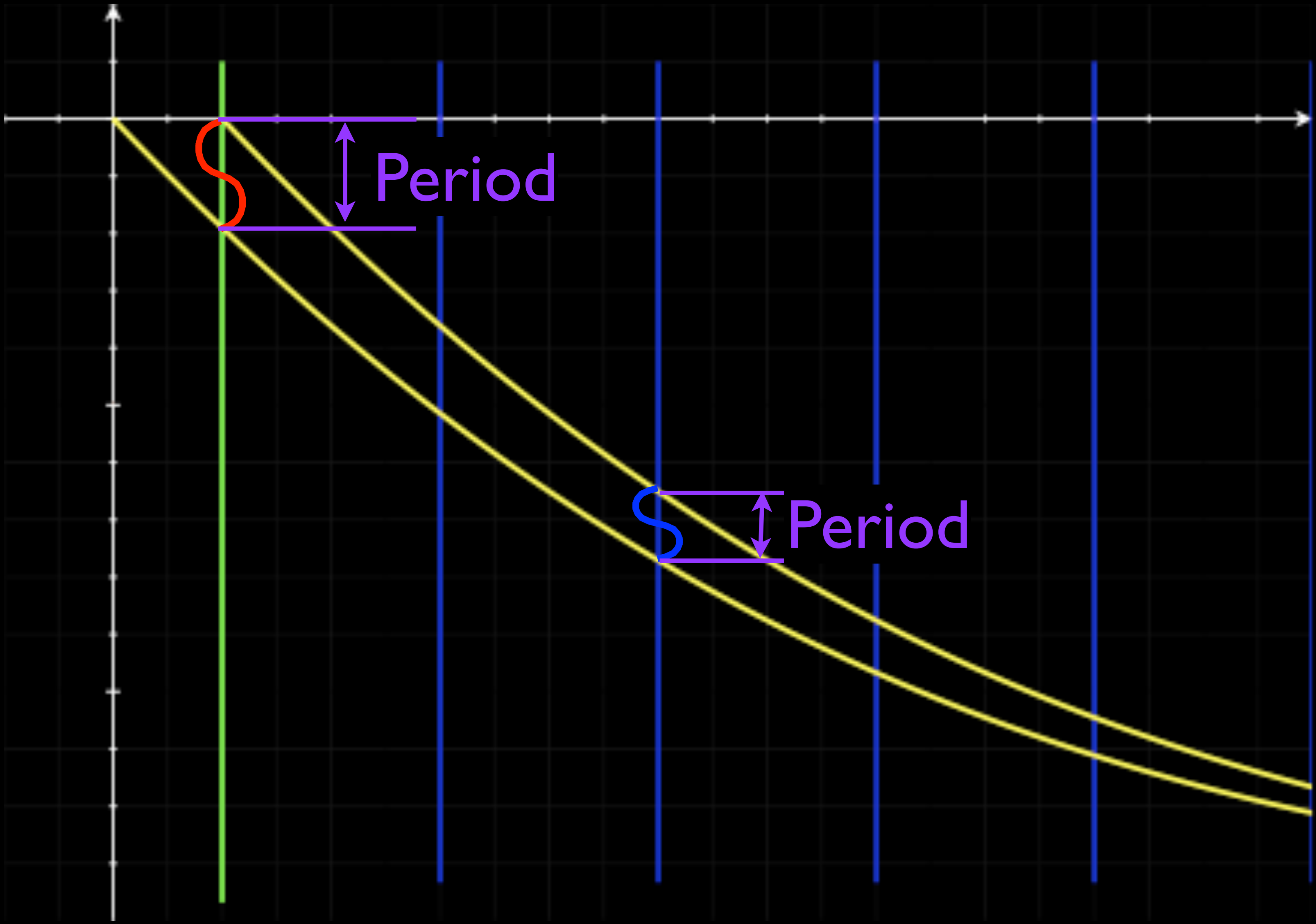
Cosmological Red Shift



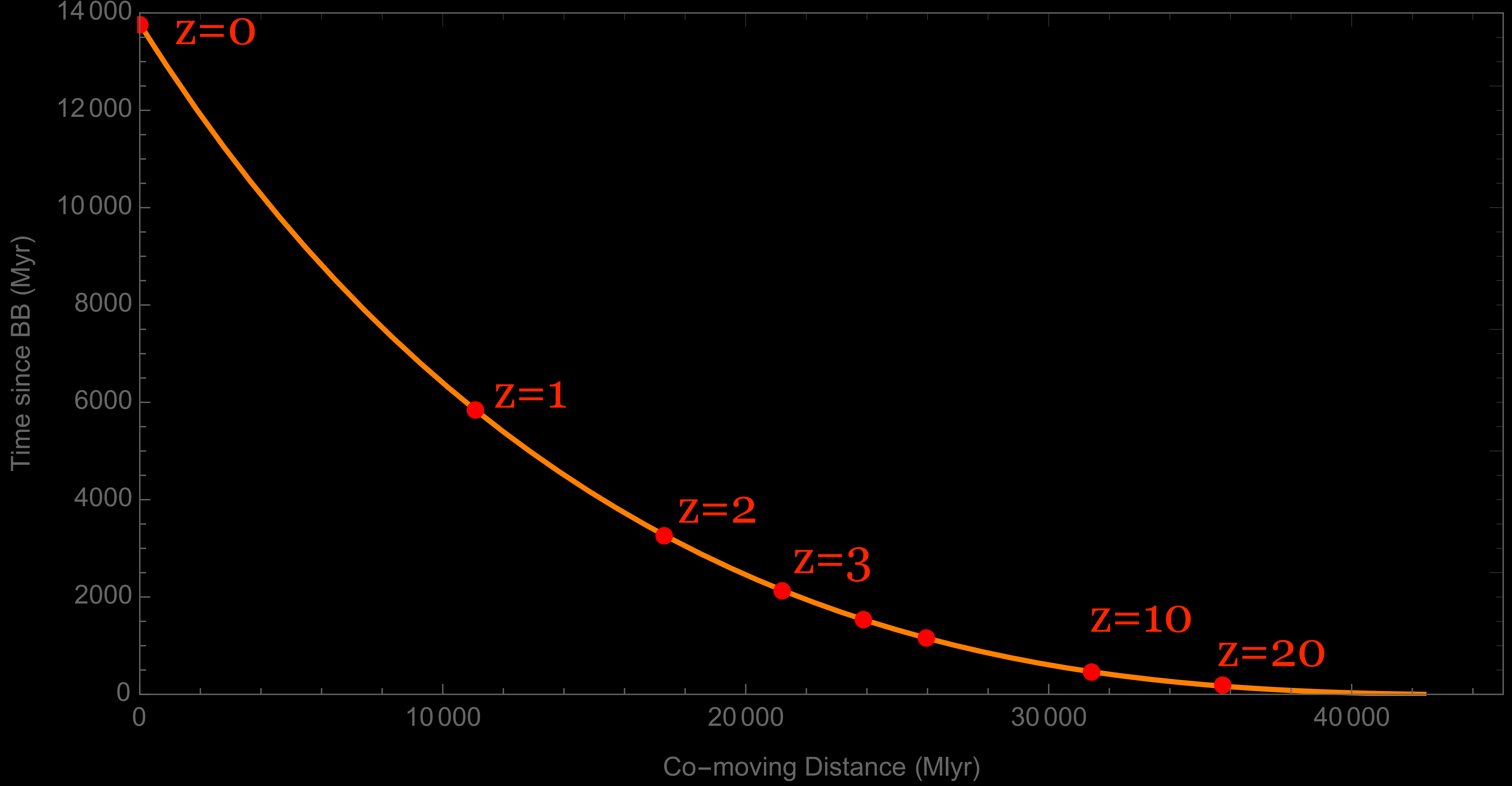
Cosmological Red Shift



Cosmological Red Shift

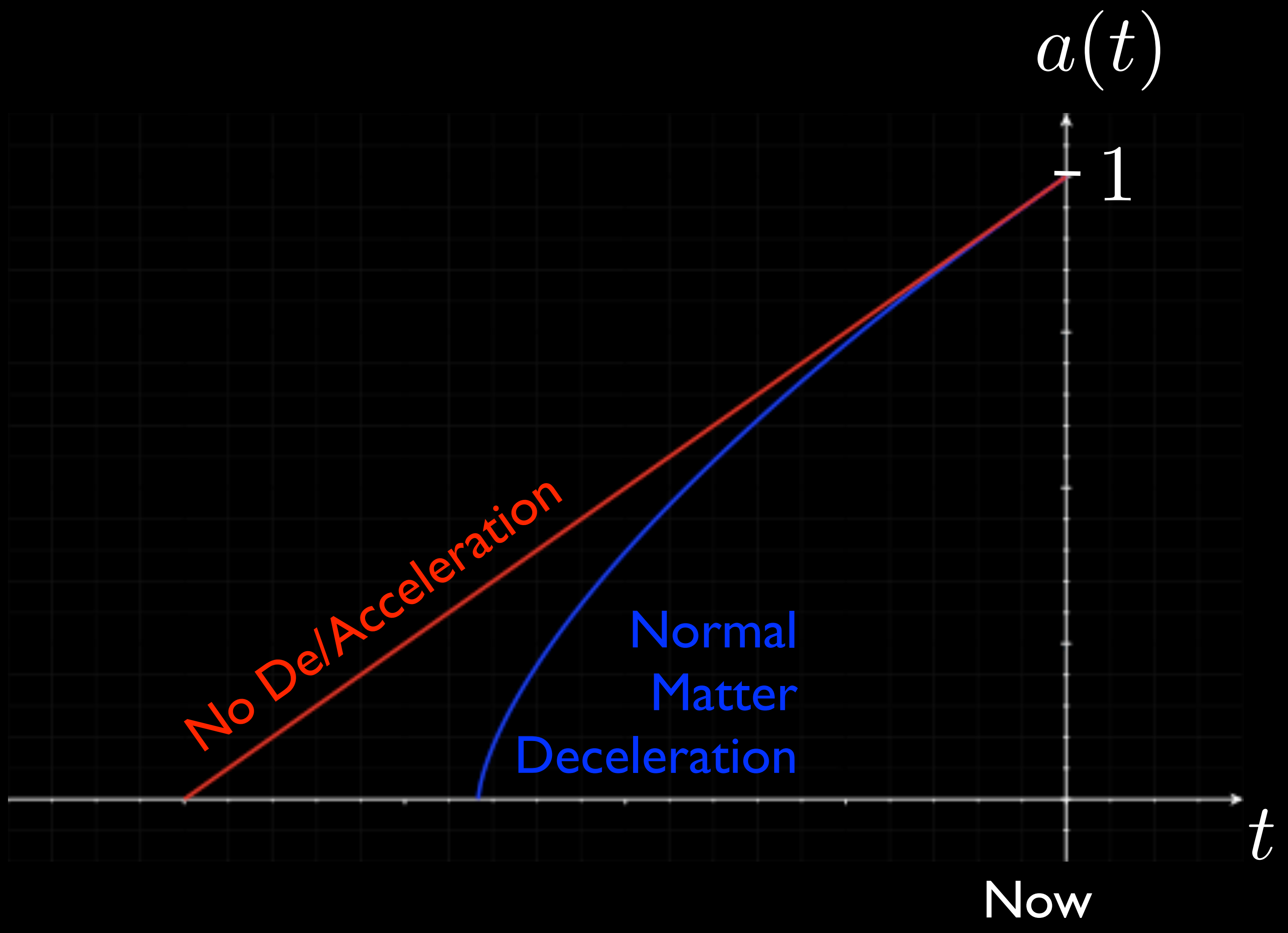


$$\lambda(t_{\text{Observed}})/\lambda(t_{\text{Emitted}}) = a(t_{\text{Observed}})/a(t_{\text{Emitted}})$$

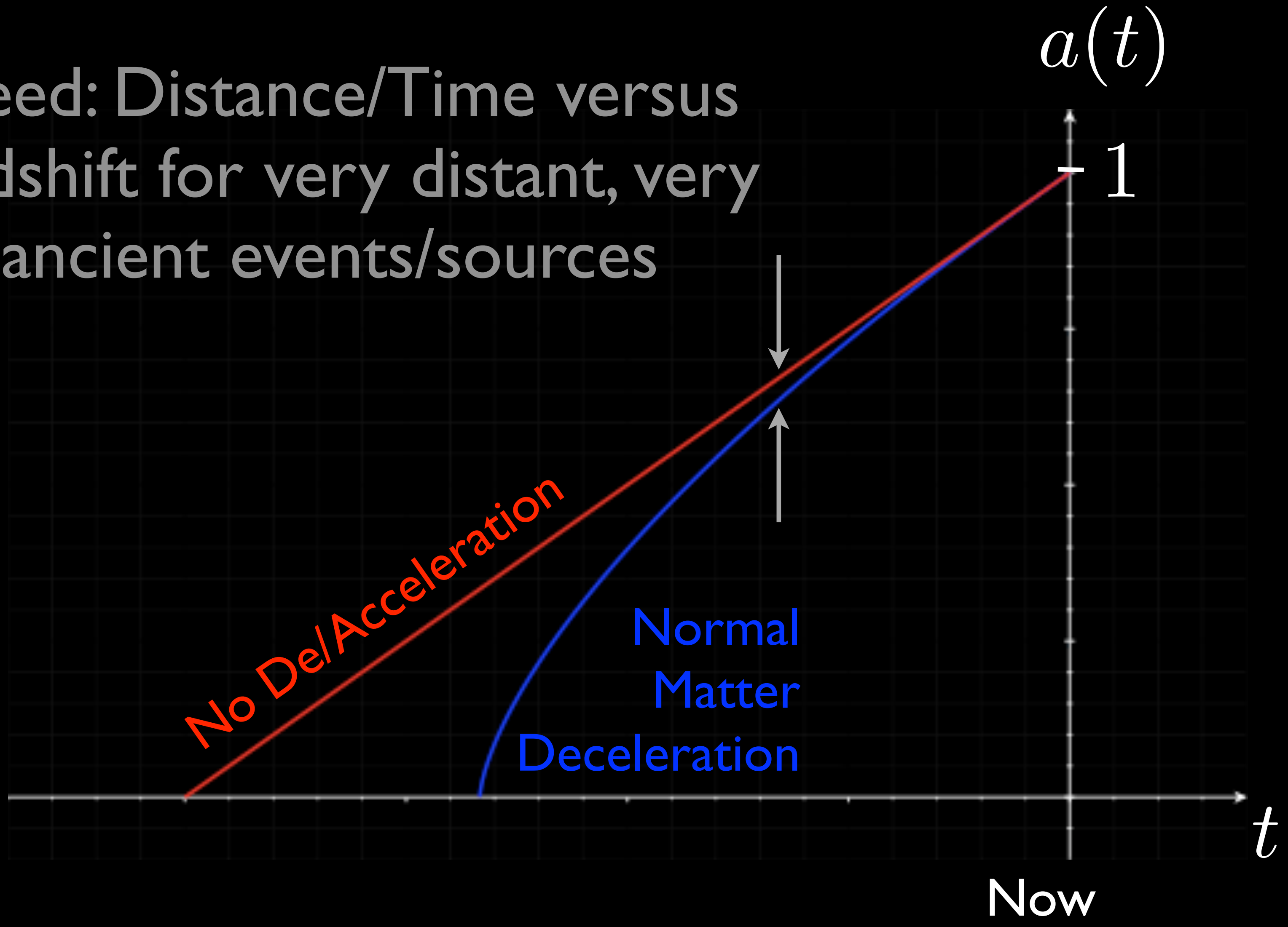

14 000
12 000
10 000
8000
6000
4000
2000
0
Time since BB (Myr)
0
10 000
20 000
30 000
40 000
Co–moving Distance (Mlyr)
z=0
z=1
z=2
z=3
z=10
z=20

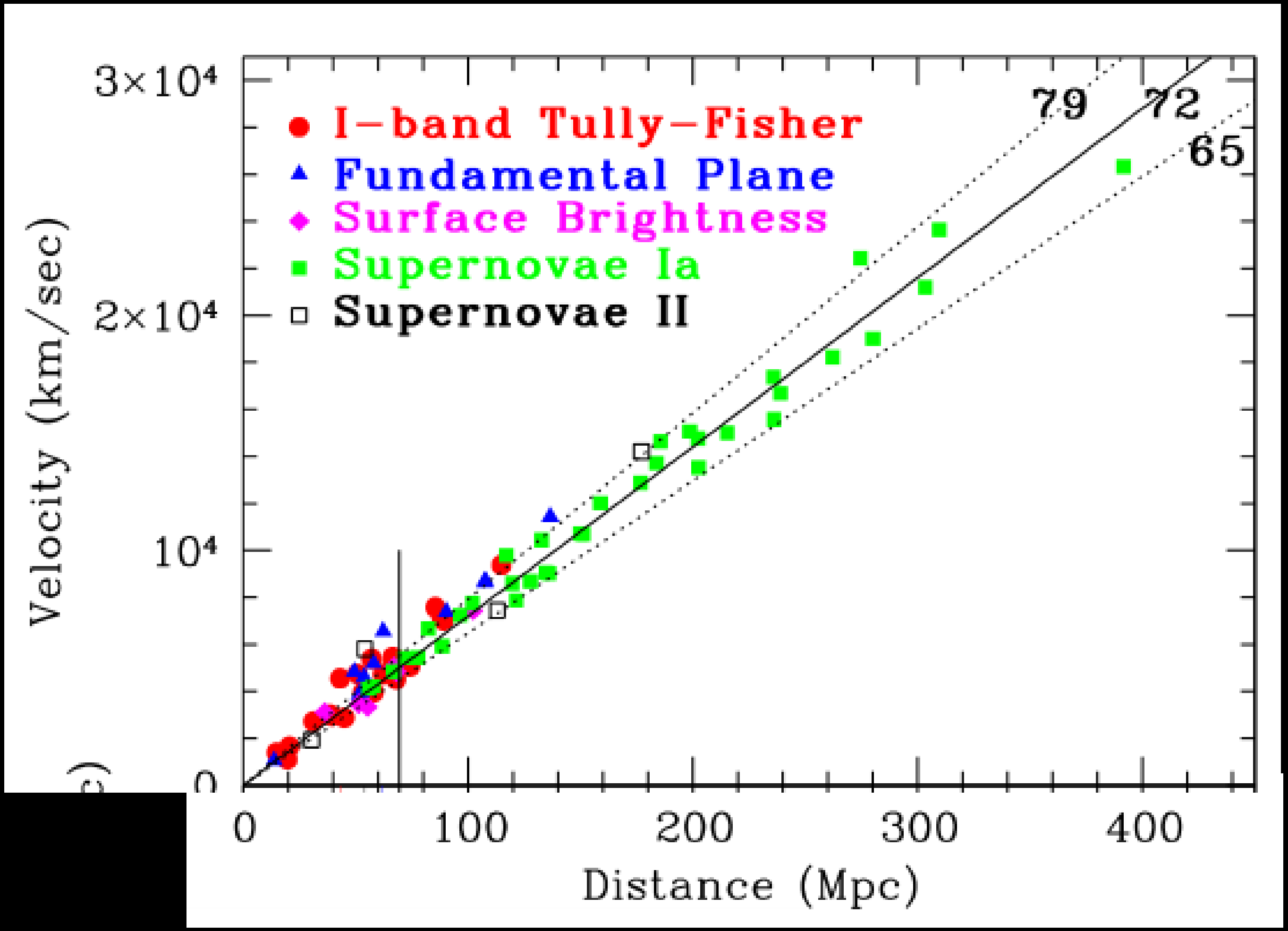
The *Accelerating* Universe

Part 2

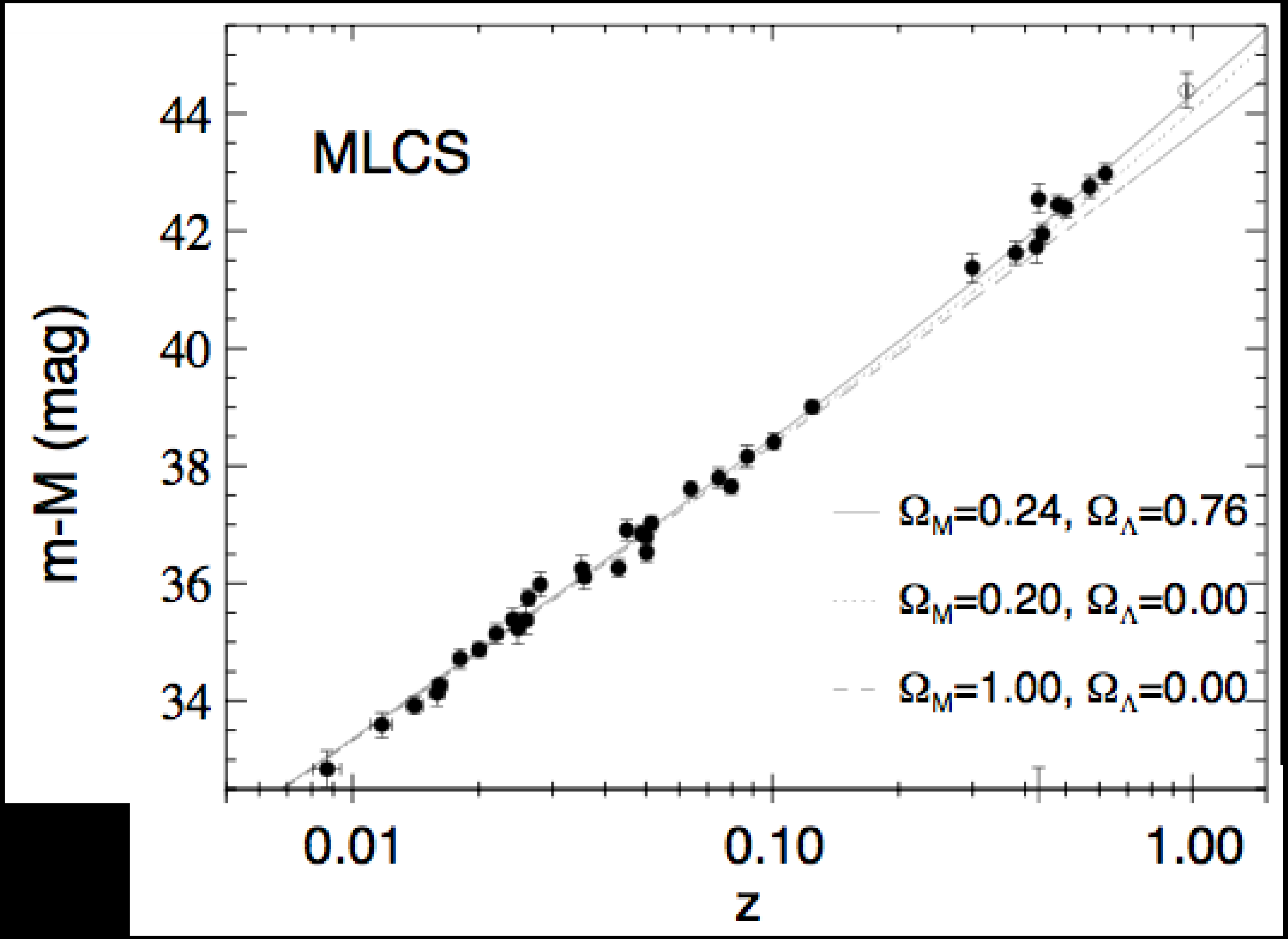

$a(t)$
1
No De/Acceleration
Normal Matter Deceleration
t
Now

Need: Distance/Time versus Redshift for very distant, very ancient events/sources





Freedman, et al. Astrophys. J.
553, 47 (2001)

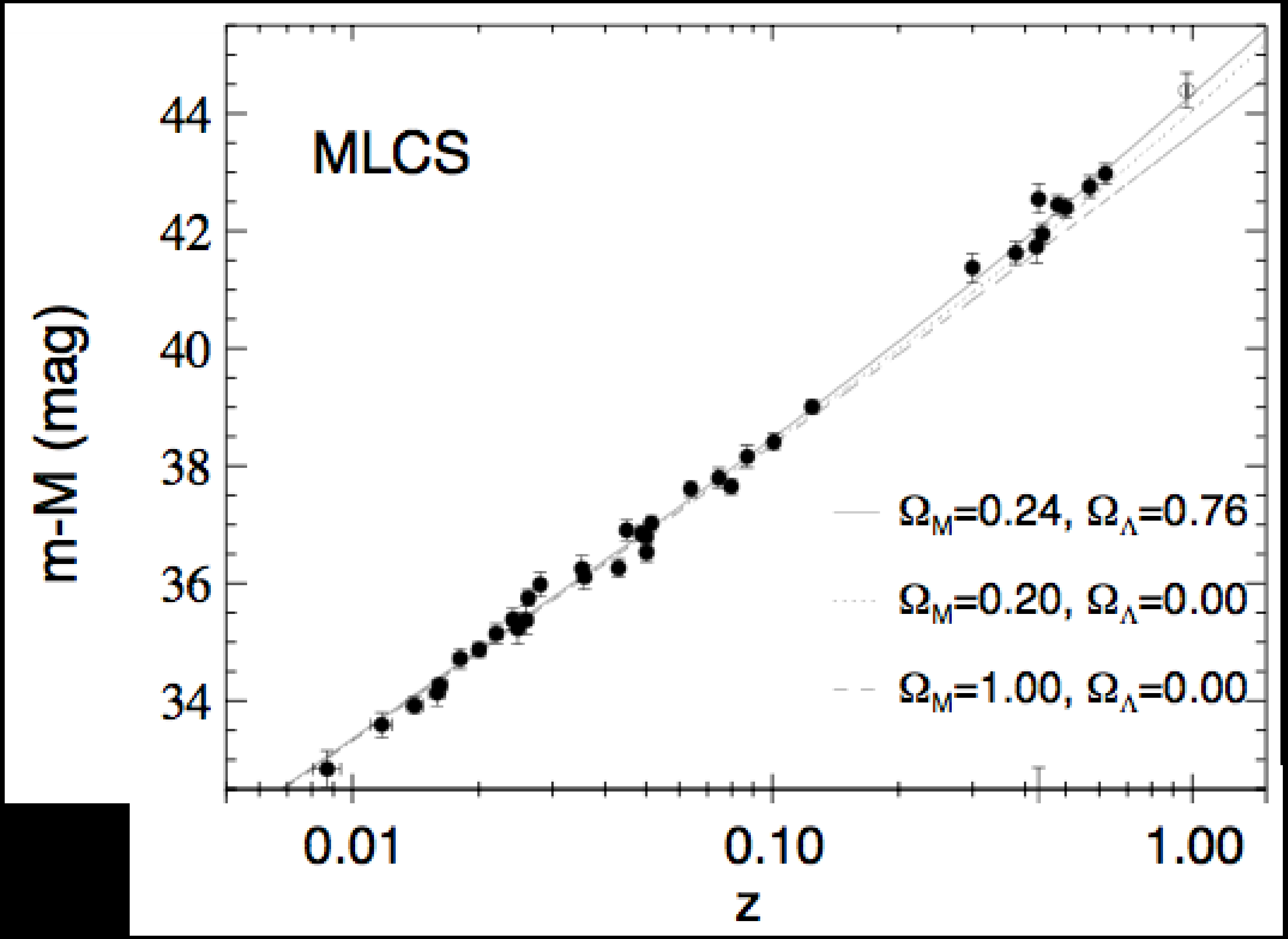


Riess, *et al.* (High-Z)
Astron. J. **116** (1998)

A. Riess
American

Supernovae
cosmology (1998)

Apparent Magnitude - Intrinsic Magnitude



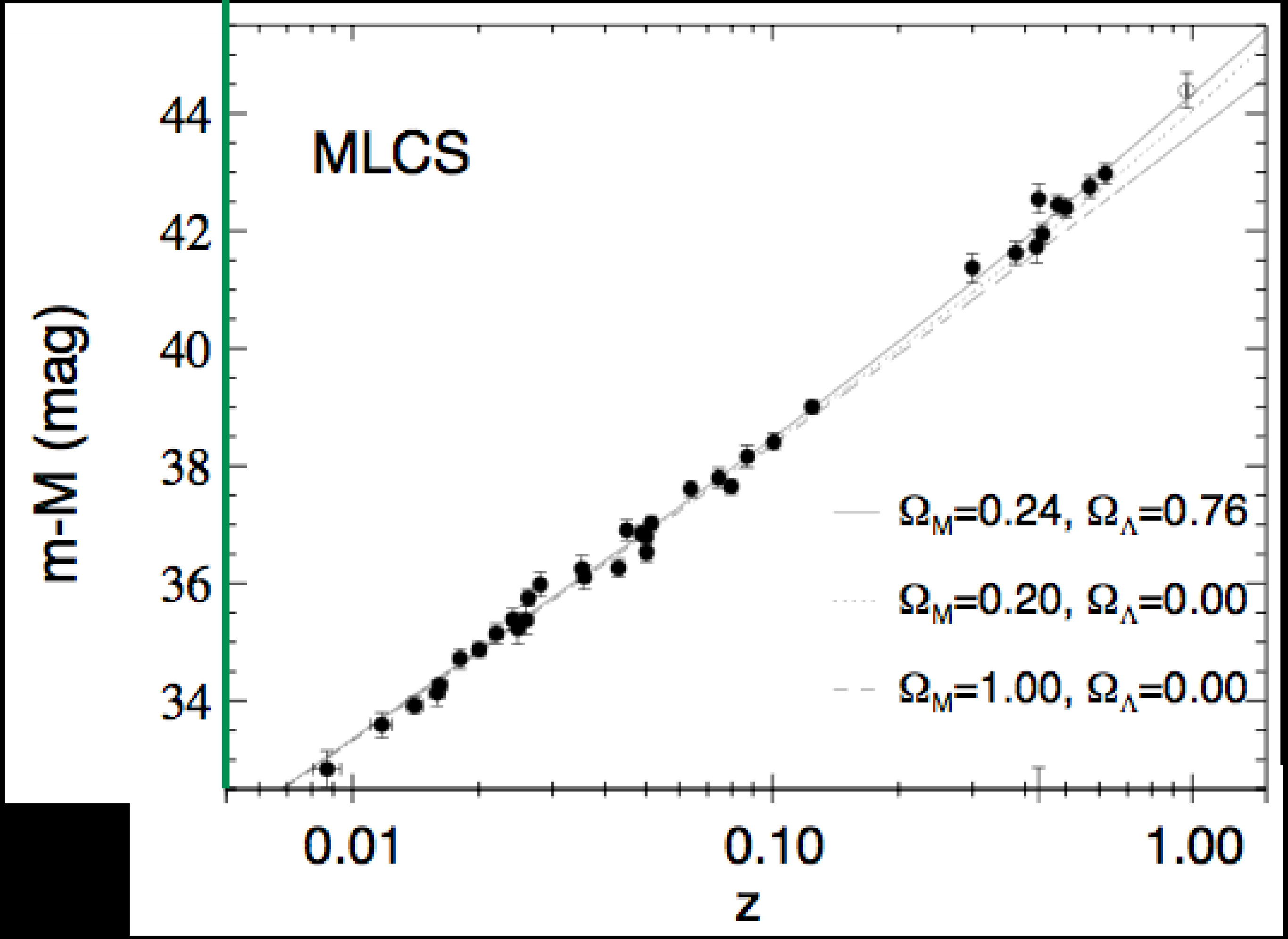
Riess, *et al.* (High-Z)
Astron. J. **116** (1998)

A. Riess
American

Supernovae
cosmology (1998)

~log(Distance)

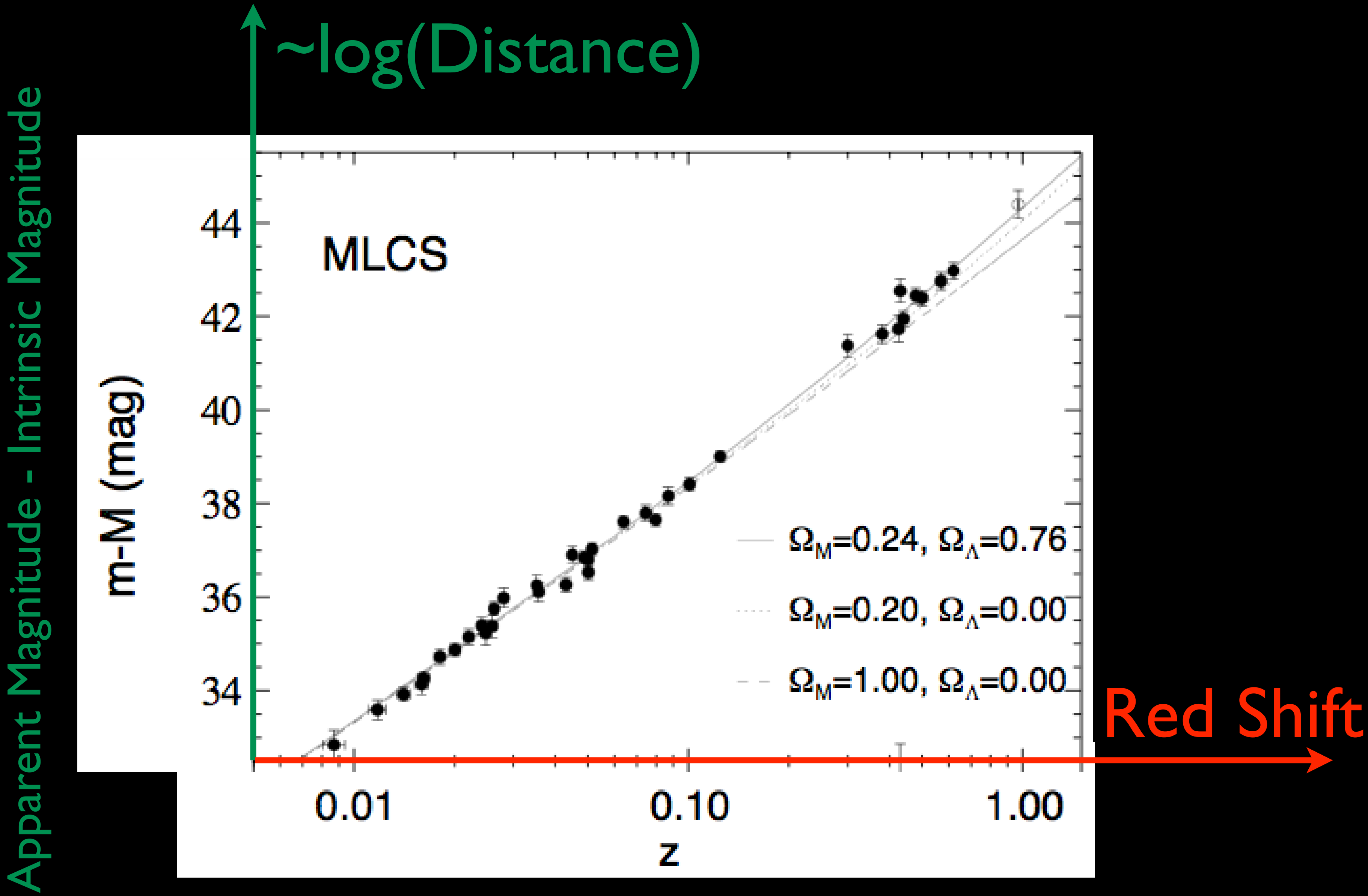
Apparent Magnitude - Intrinsic Magnitude



Riess, *et al.* (High-Z)
Astron. J. **116** (1998)

A. Riess
American

Supernovae
cosmology (1998)



~log(Distance)

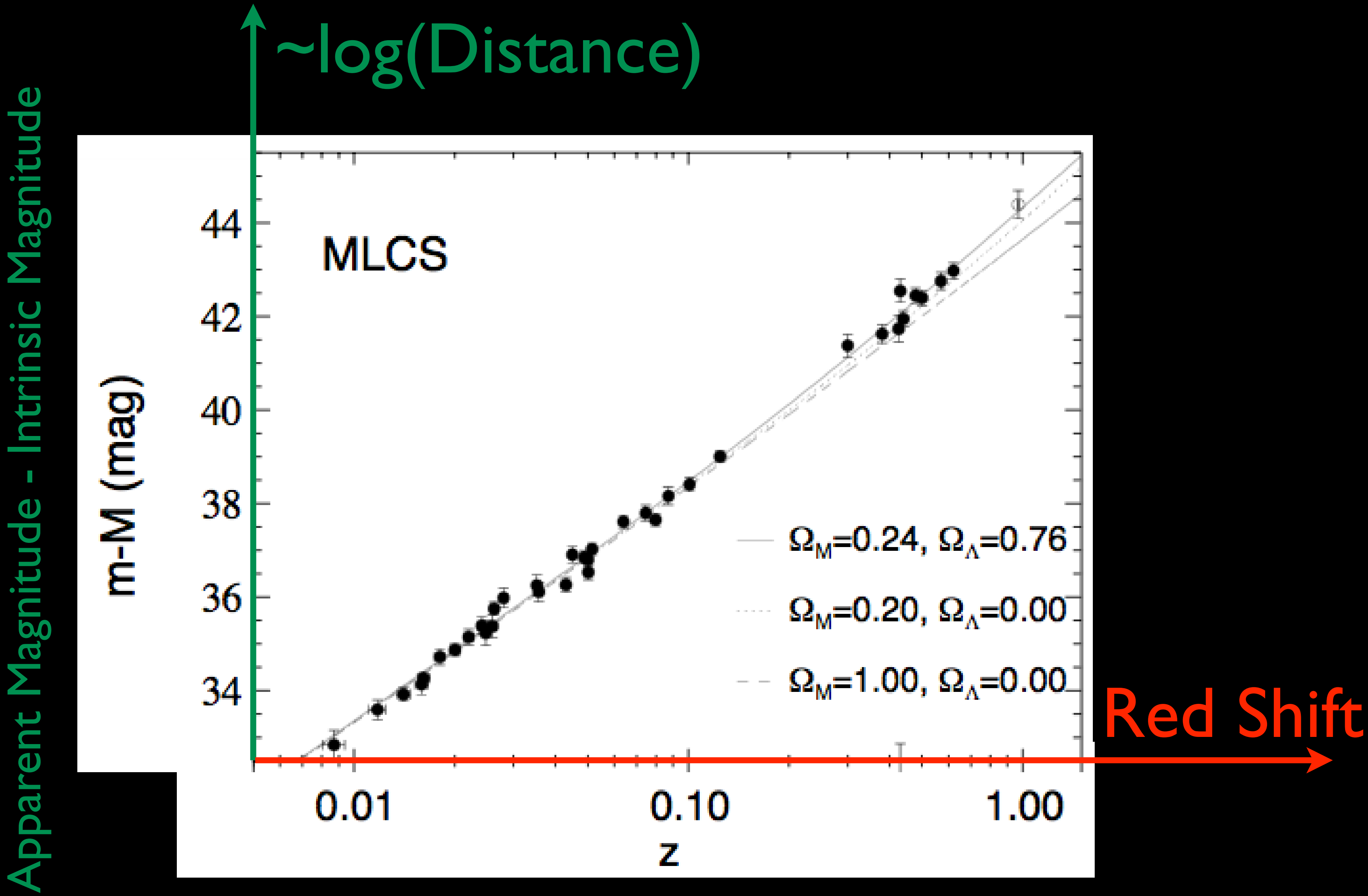
Apparent Magnitude - Intrinsic Magnitude

Red Shift

Riess, *et al.* (High-Z)
Astron. J. **116** (1998)

A. Riess
American

Supernovae
cosmology (1998)



~log(Distance)

Apparent Magnitude - Intrinsic Magnitude

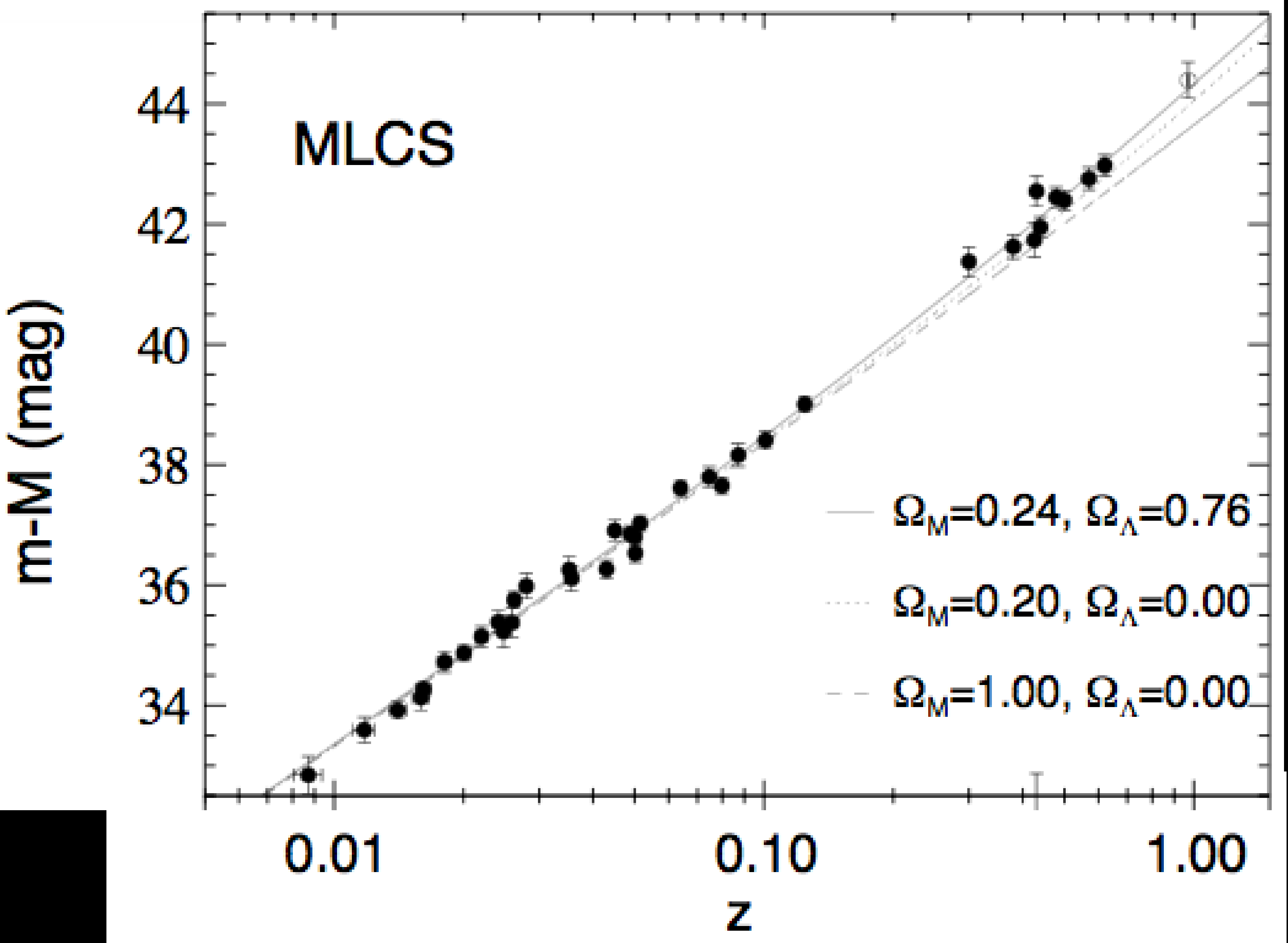
Red Shift

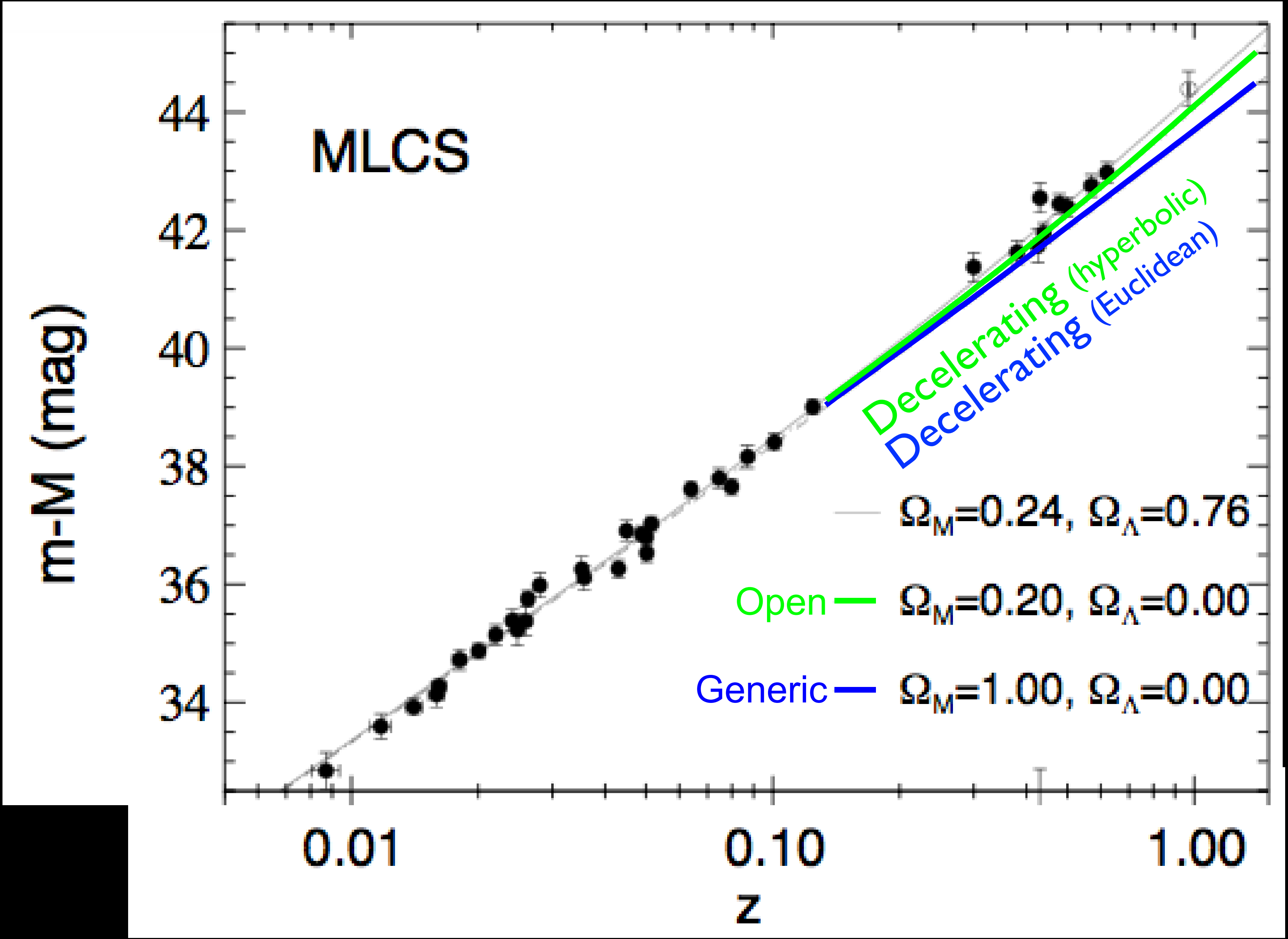
Riess, *et al.* (High-Z)
Astron. J. **116** (1998)

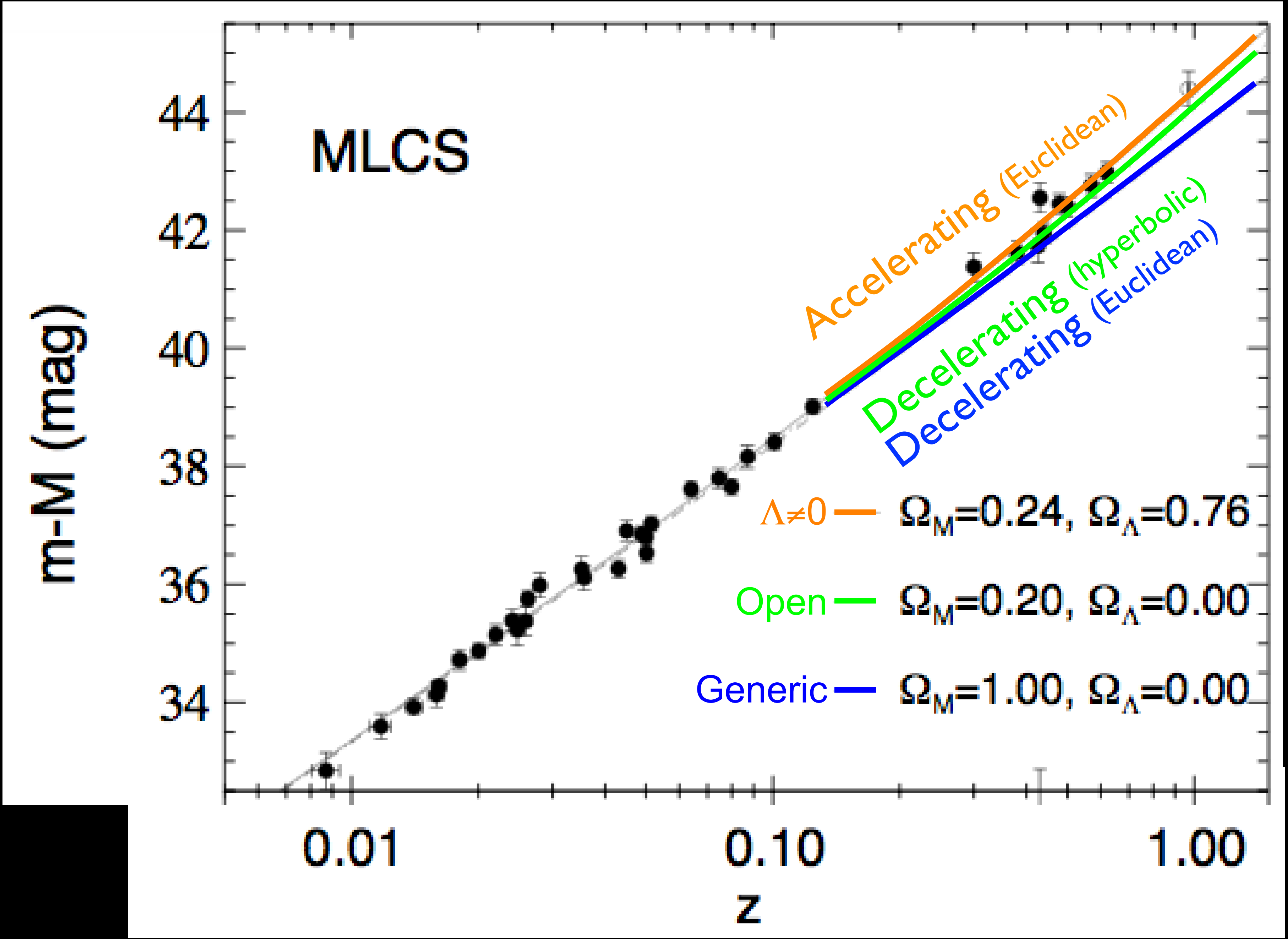
A. Riess
American

Supernovae
cosmology (1998)

$$z = \frac{\lambda(t_{\text{Observed}})}{\lambda(t_{\text{Emitted}})} - 1 \approx v/c$$

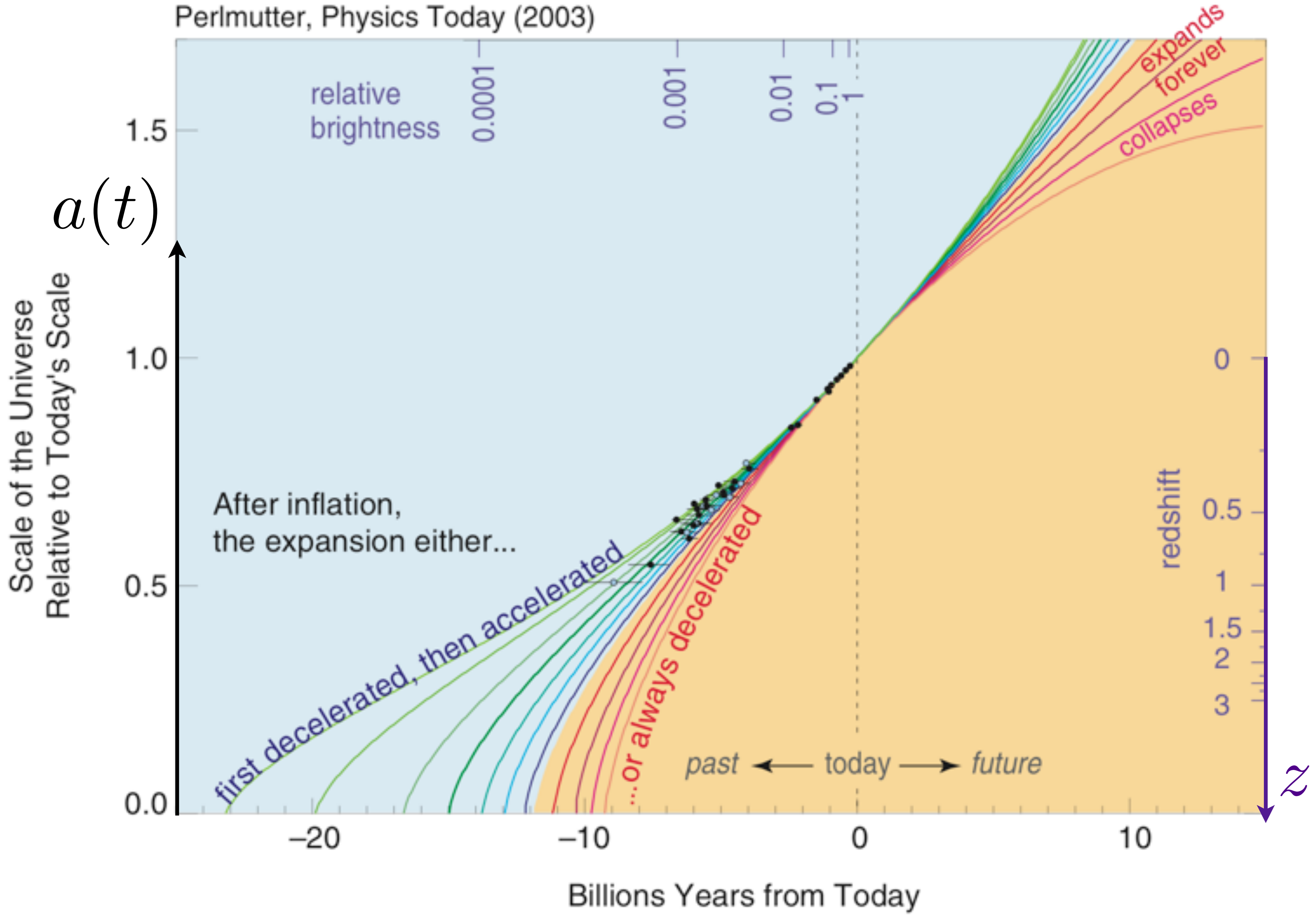

MLCS
m-M (mag)
44
42
40
38
36
34
0.01
0.10
1.00
z
Ω_M=0.24, Ω_Λ=0.76
Ω_M=0.20, Ω_Λ=0.00
Ω_M=1.00, Ω_Λ=0.00


MLCS
m-M (mag)
44
42
40
38
36
34
0.01
0.10
1.00
z
Decelerating (hyperbolic)
Decelerating (Euclidean)
Ω_M=0.24, Ω_Λ=0.76
Open — Ω_M=0.20, Ω_Λ=0.00
Generic — Ω_M=1.00, Ω_Λ=0.00


MLCS
m-M (mag)
44
42
40
38
36
34
0.01
0.10
1.00
z
Accelerating (Euclidean)
Decelerating (hyperbolic)
Decelerating (Euclidean)
Λ≠0 — Ω_M=0.24, Ω_Λ=0.76
Open — Ω_M=0.20, Ω_Λ=0.00
Generic — Ω_M=1.00, Ω_Λ=0.00

Expansion History of the Universe

Perlmutter, Physics Today (2003)



Expansion Dynamics

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\mathrm{N}}}{3c^2}\left[\rho(t) + 3P(t)\right]$$

The Friedmann
Equation

Expansion Dynamics

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\mathrm{N}}}{3c^2}\left[\rho(t) + 3P(t)\right]$$

⇧

Mass-Energy
Density

The Friedmann
Equation

Expansion Dynamics

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\mathrm{N}}}{3c^2}\left[\rho(t) + 3P(t)\right]$$

Mass-Energy Density

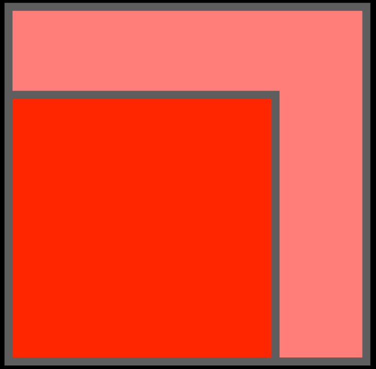
Pressure

The Friedmann Equation

Negative Pressure (?)

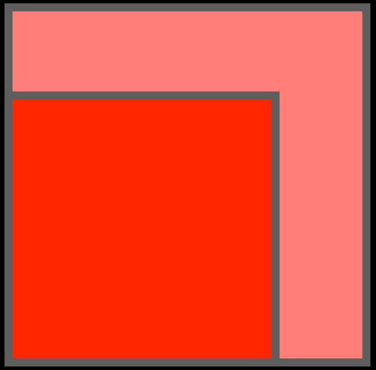
🟥 Radiation

Negative Pressure (?)

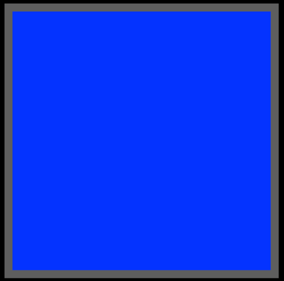


Radiation $P = -\frac{\partial E}{\partial V} = +\rho/3$

Negative Pressure (?)

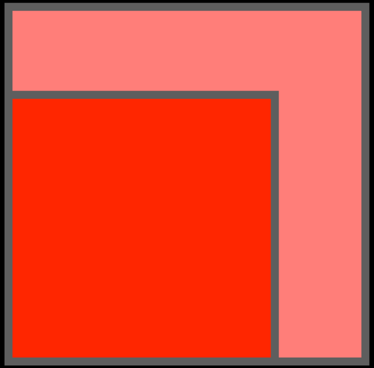


Radiation $P = -\frac{\partial E}{\partial V} = +\rho/3$



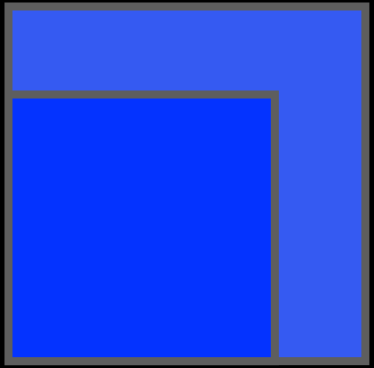
Matter

Negative Pressure (?)



Radiation

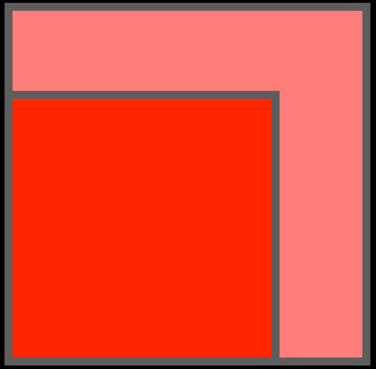
$$P = -\frac{\partial E}{\partial V} = +\rho/3$$



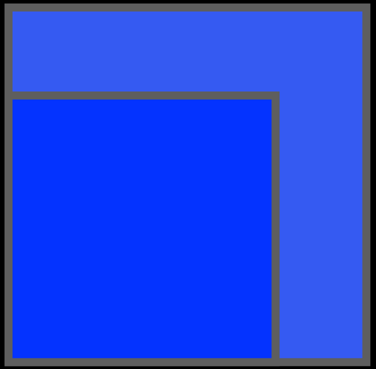
Matter

$$P = -\frac{\partial E}{\partial V} \sim 0$$

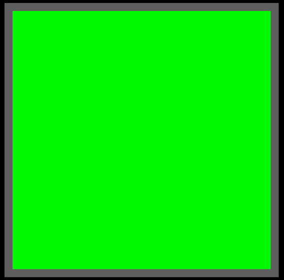
Negative Pressure (?)



Radiation $P = -\frac{\partial E}{\partial V} = +\rho/3$

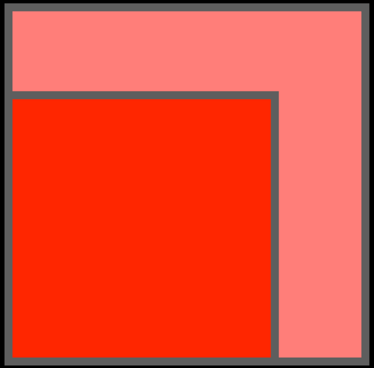


Matter $P = -\frac{\partial E}{\partial V} \sim 0$



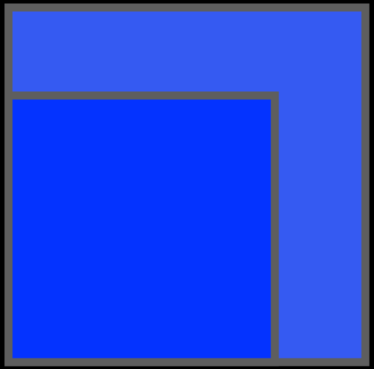
Vacuum
Energy

Negative Pressure (?)



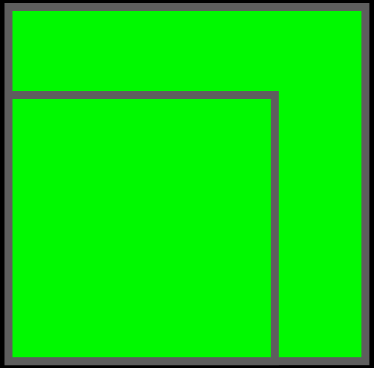
Radiation

$$P = -\frac{\partial E}{\partial V} = +\rho/3$$



Matter

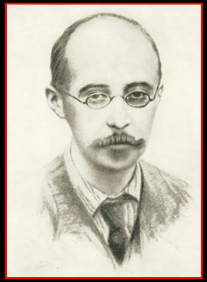
$$P = -\frac{\partial E}{\partial V} \sim 0$$

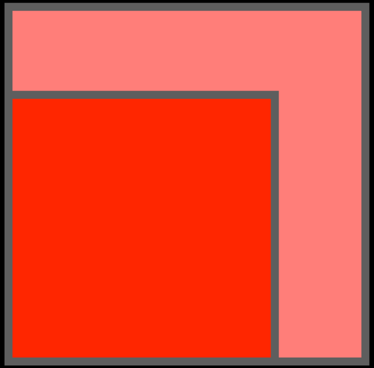


Vacuum Energy

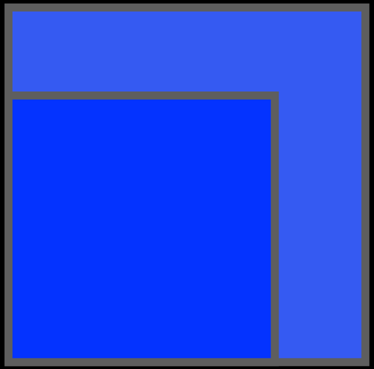
$$P = -\frac{\partial E}{\partial V} = -\rho$$

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\rm N}}{3c^2}\left[\rho(t) + 3P(t)\right]$$

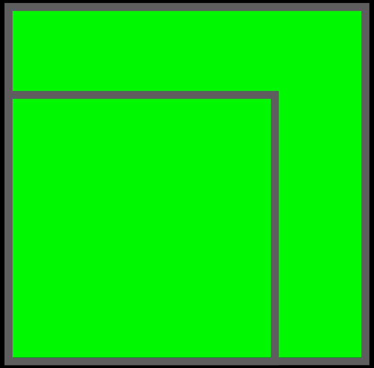




Radiation

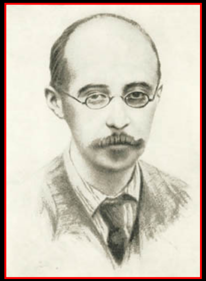


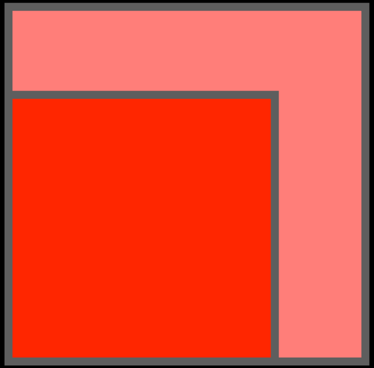
Matter



Vacuum Energy

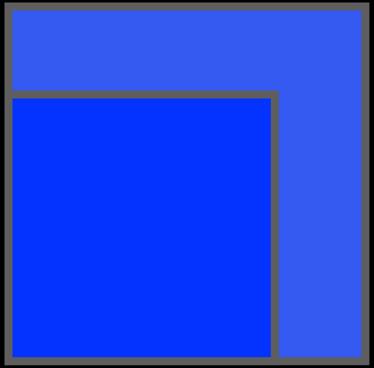
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\mathrm{N}}}{3c^2}\left[\rho(t) + 3P(t)\right]$$



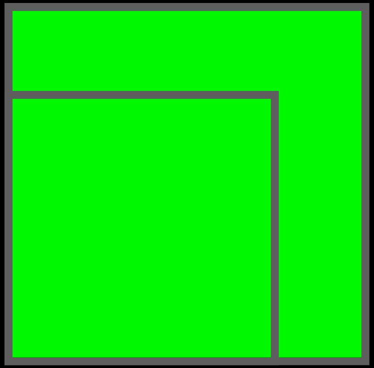


Radiation

$$a(t) \propto t^{1/2}$$

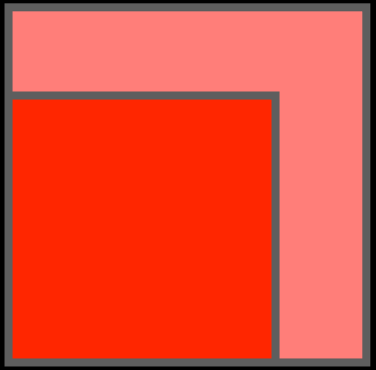


Matter



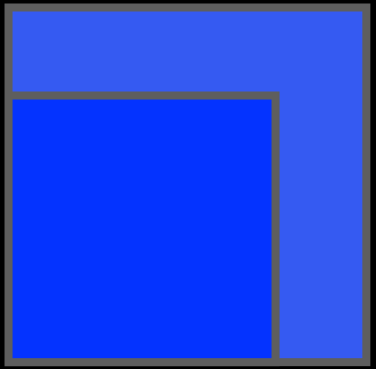
Vacuum Energy

$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\mathrm{N}}}{3c^2}\left[\rho(t) + 3P(t)\right]$$



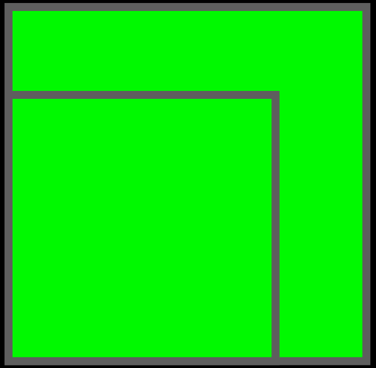
Radiation

$$a(t) \propto t^{1/2}$$



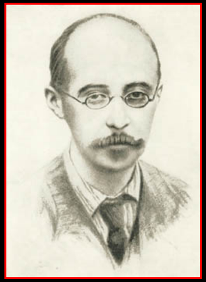
Matter

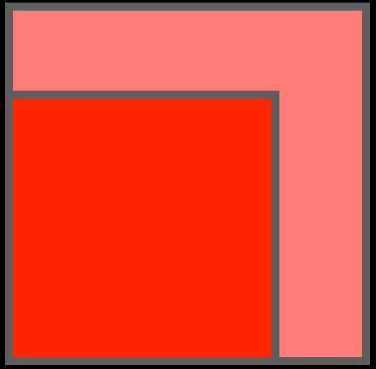
$$a(t) \propto t^{2/3}$$



Vacuum
Energy

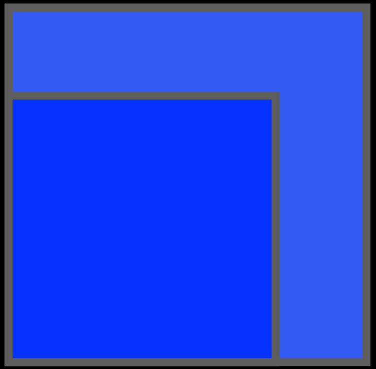
$$\frac{\ddot{a}(t)}{a(t)} = -\frac{4\pi G_{\mathrm{N}}}{3c^2}\left[\rho(t) + 3P(t)\right]$$





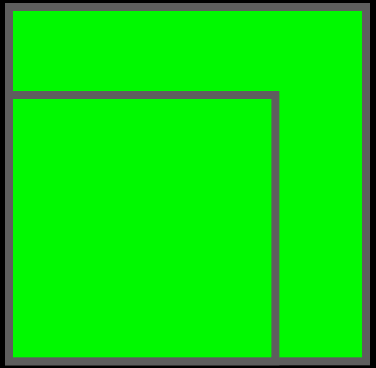
Radiation

$$a(t) \propto t^{1/2}$$



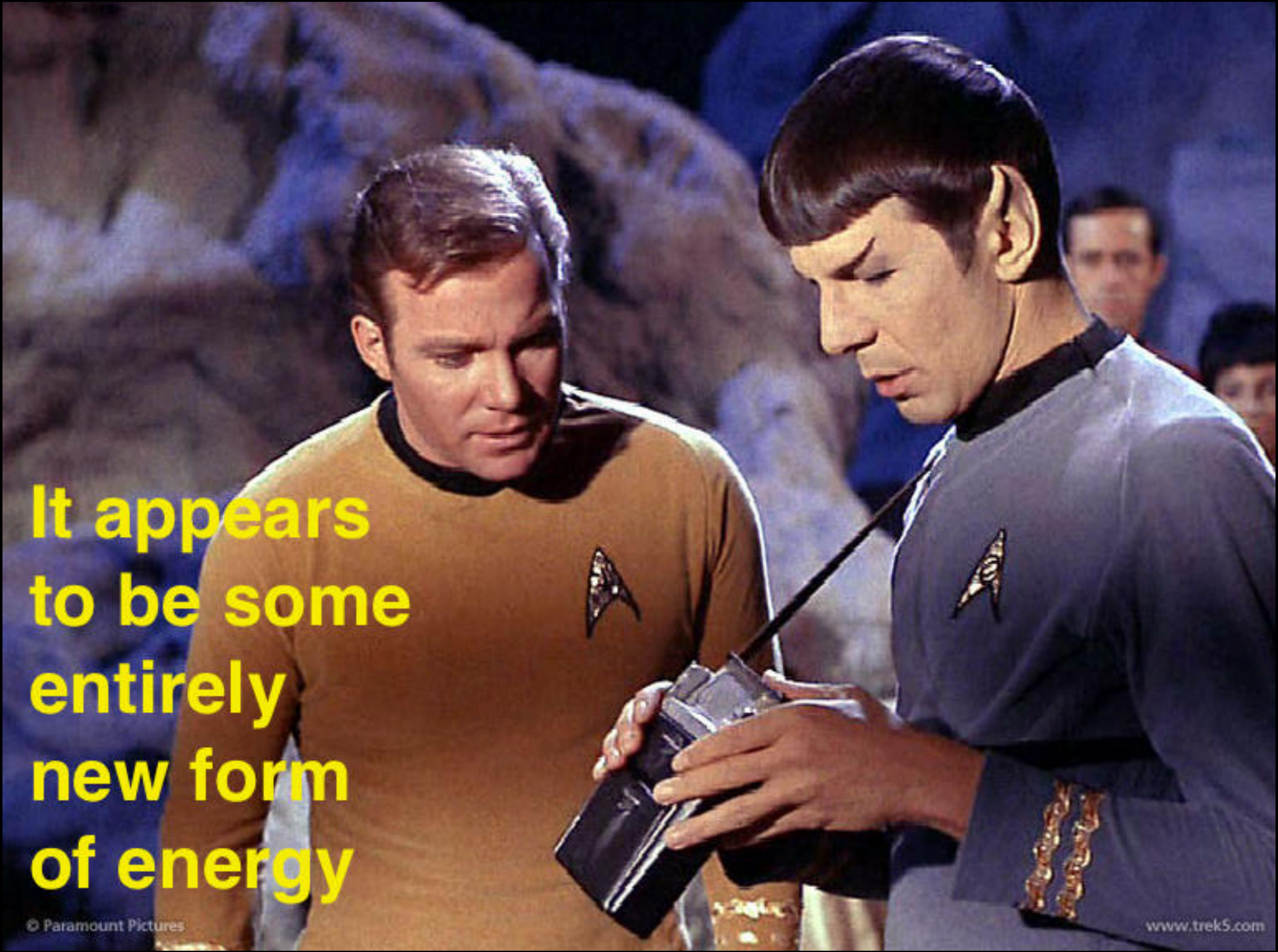
Matter

$$a(t) \propto t^{2/3}$$



Vacuum
Energy

$$a(t) \propto e^{H_0\, t}$$



It appears to be some entirely new form of energy

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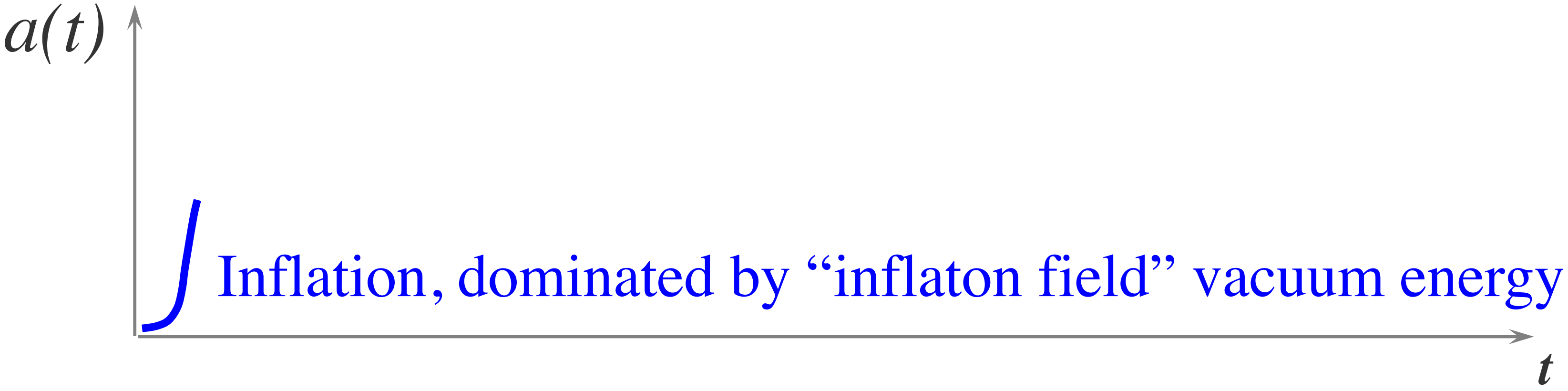
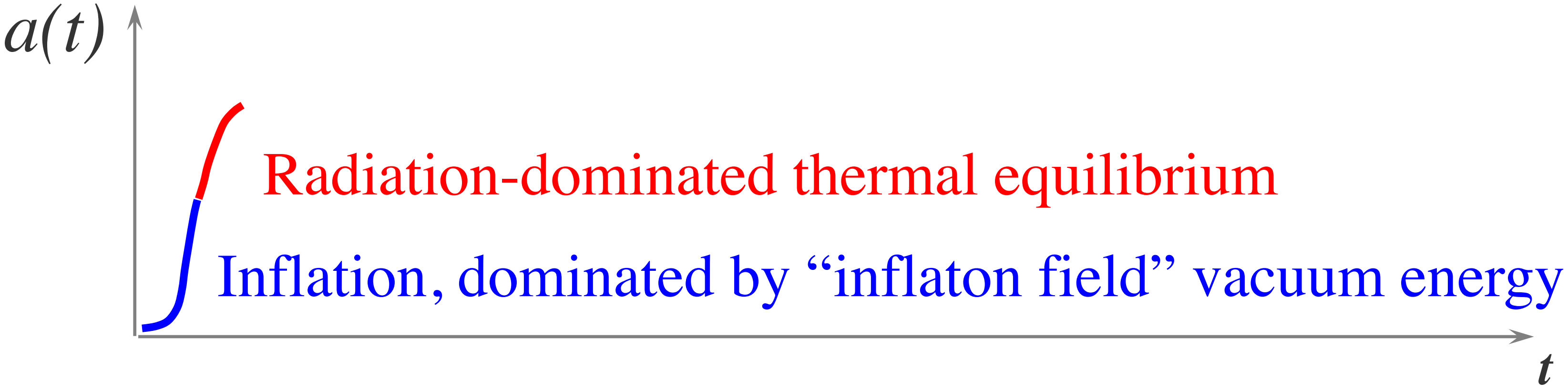


Inflation, dominated by “inflaton field” vacuum energy

The New Standard Cosmology in Four Easy Steps

$a(t) \propto e^{Ht}$



Radiation-dominated thermal equilibrium

Inflation, dominated by “inflaton field” vacuum energy

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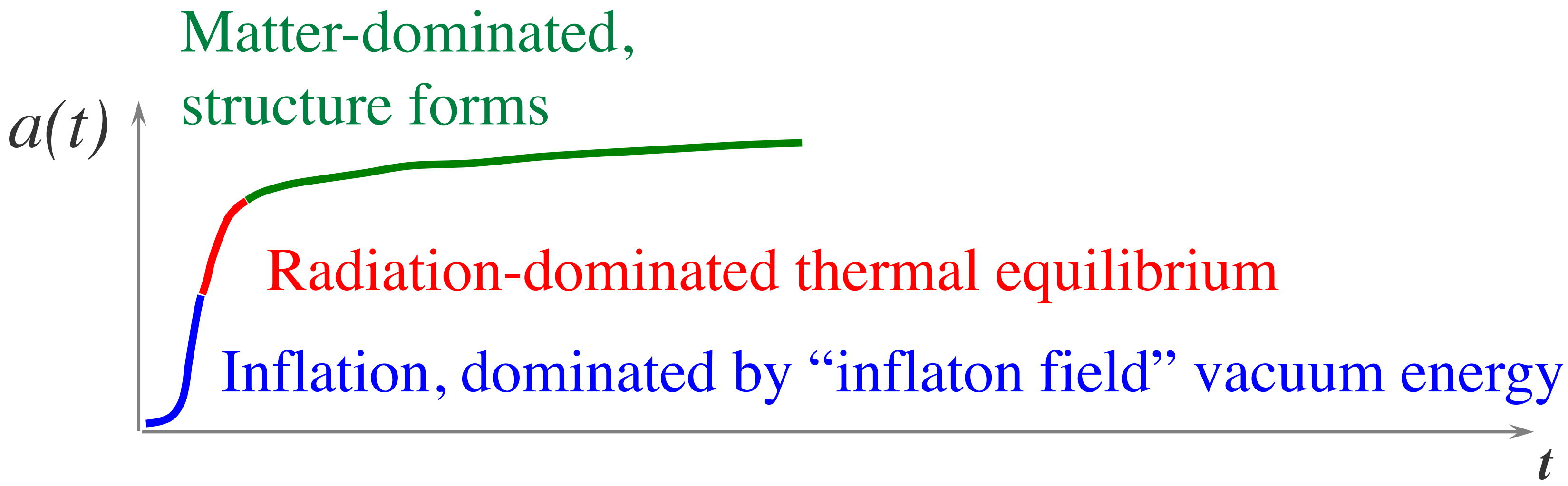

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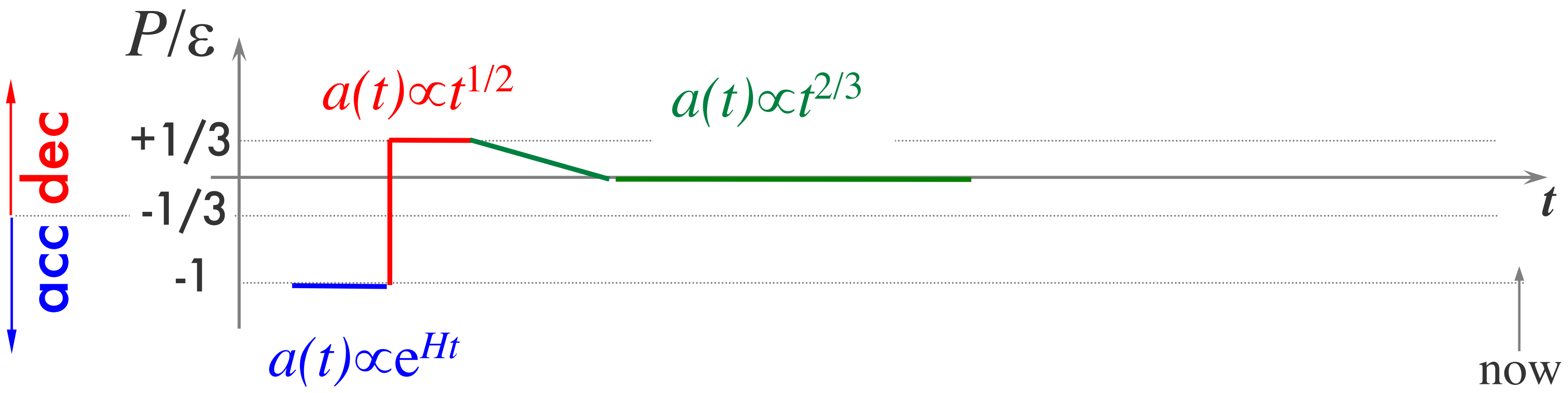

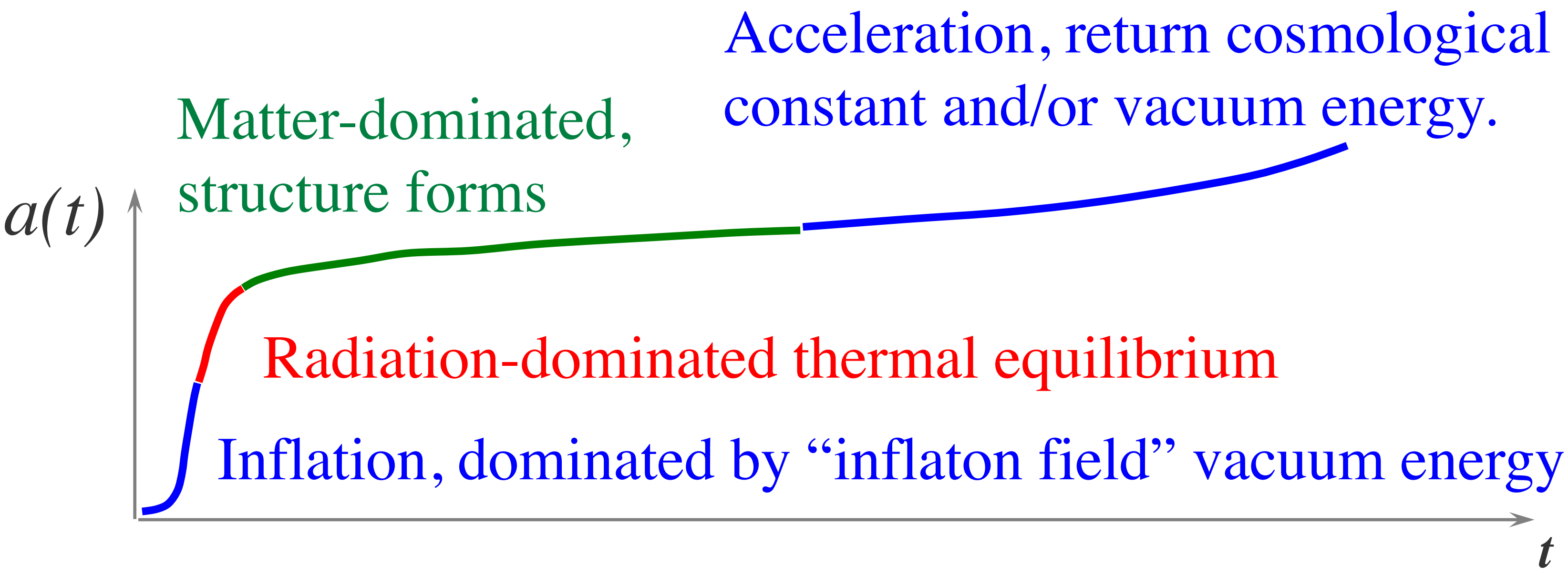

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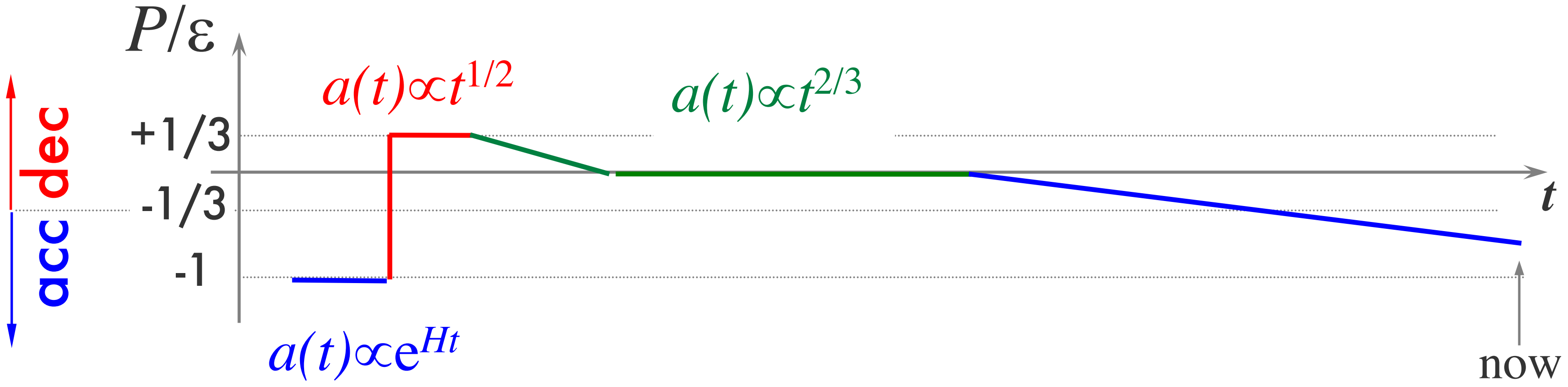
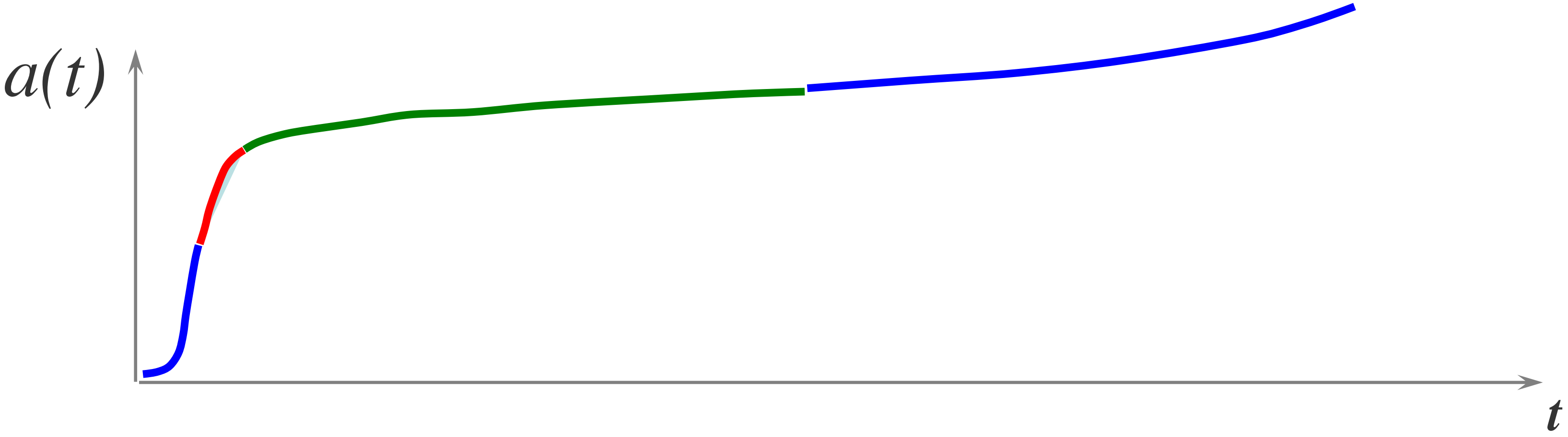
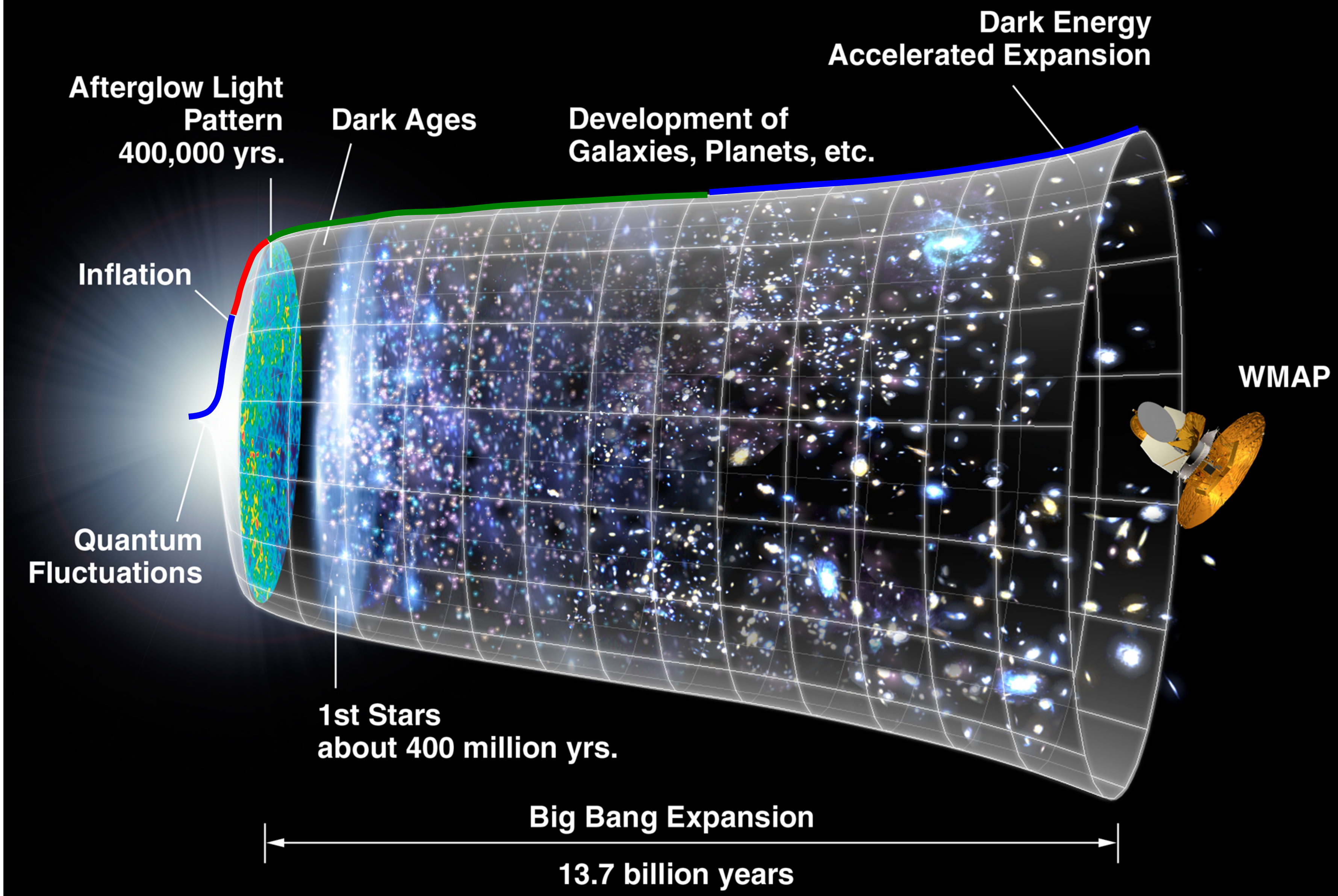
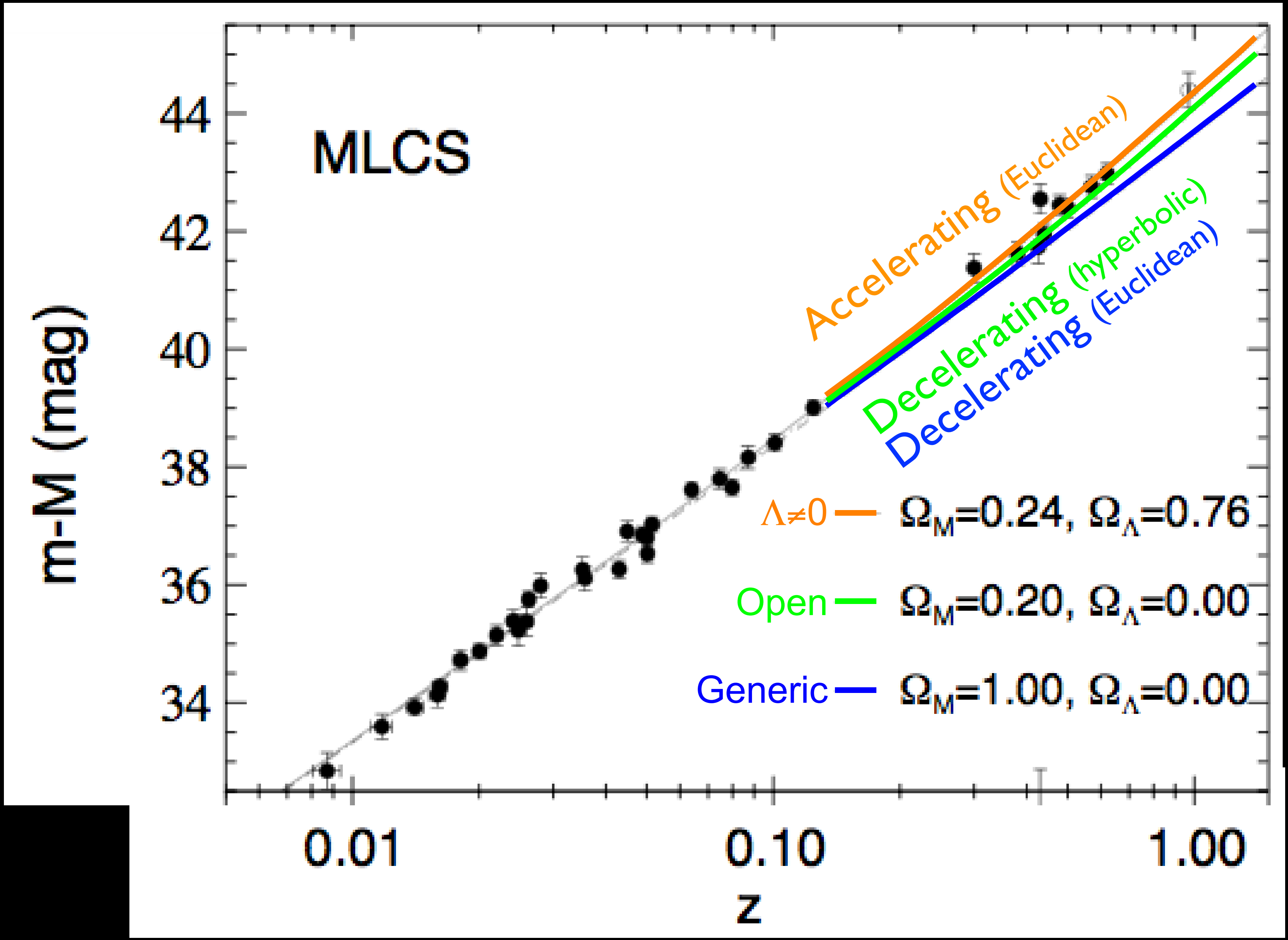
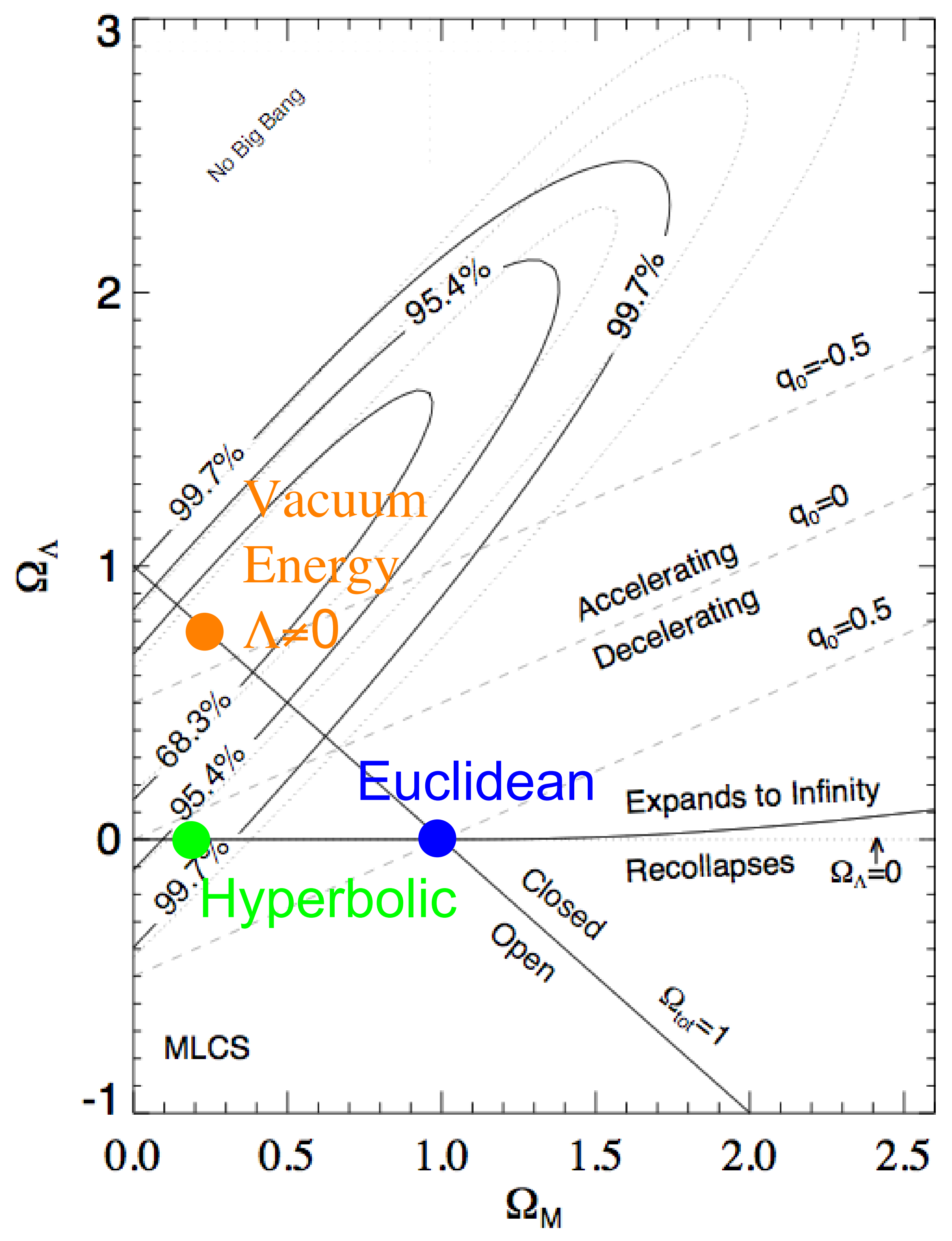
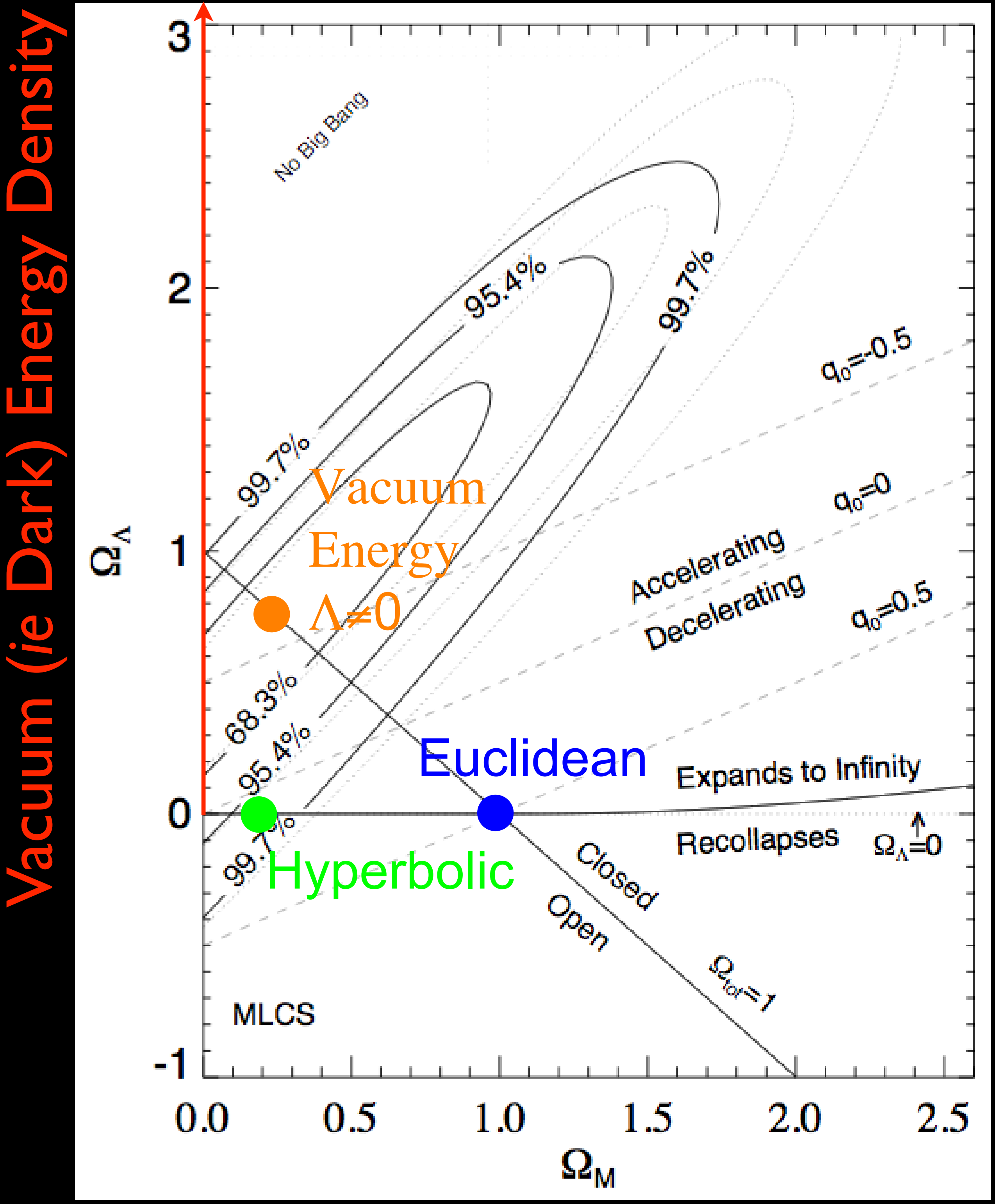



$a(t)$
t


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years


MLCS
m-M (mag)
44
42
40
38
36
34
0.01
0.10
1.00
z
Accelerating (Euclidean)
Decelerating (hyperbolic)
Decelerating (Euclidean)
Λ≠0 Ω_M=0.24, Ω_Λ=0.76
Open Ω_M=0.20, Ω_Λ=0.00
Generic Ω_M=1.00, Ω_Λ=0.00


3
2
1
0
-1
Ω_Λ
0.0
0.5
1.0
1.5
2.0
2.5
Ω_M
No Big Bang
95.4%
99.7%
99.7%
Vacuum Energy $\Lambda \neq 0$
q_0=-0.5
q_0=0
q_0=0.5
Accelerating
Decelerating
68.3%
95.4%
99.7%
Euclidean
Hyperbolic
Expands to Infinity
Recollapses
Ω_Λ=0
Closed
Open
Ω_{tot}=1
MLCS


Vacuum (*ie* Dark) Energy Density
3
2
1
0
-1
Ω_Λ
No Big Bang
95.4%
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MLCS
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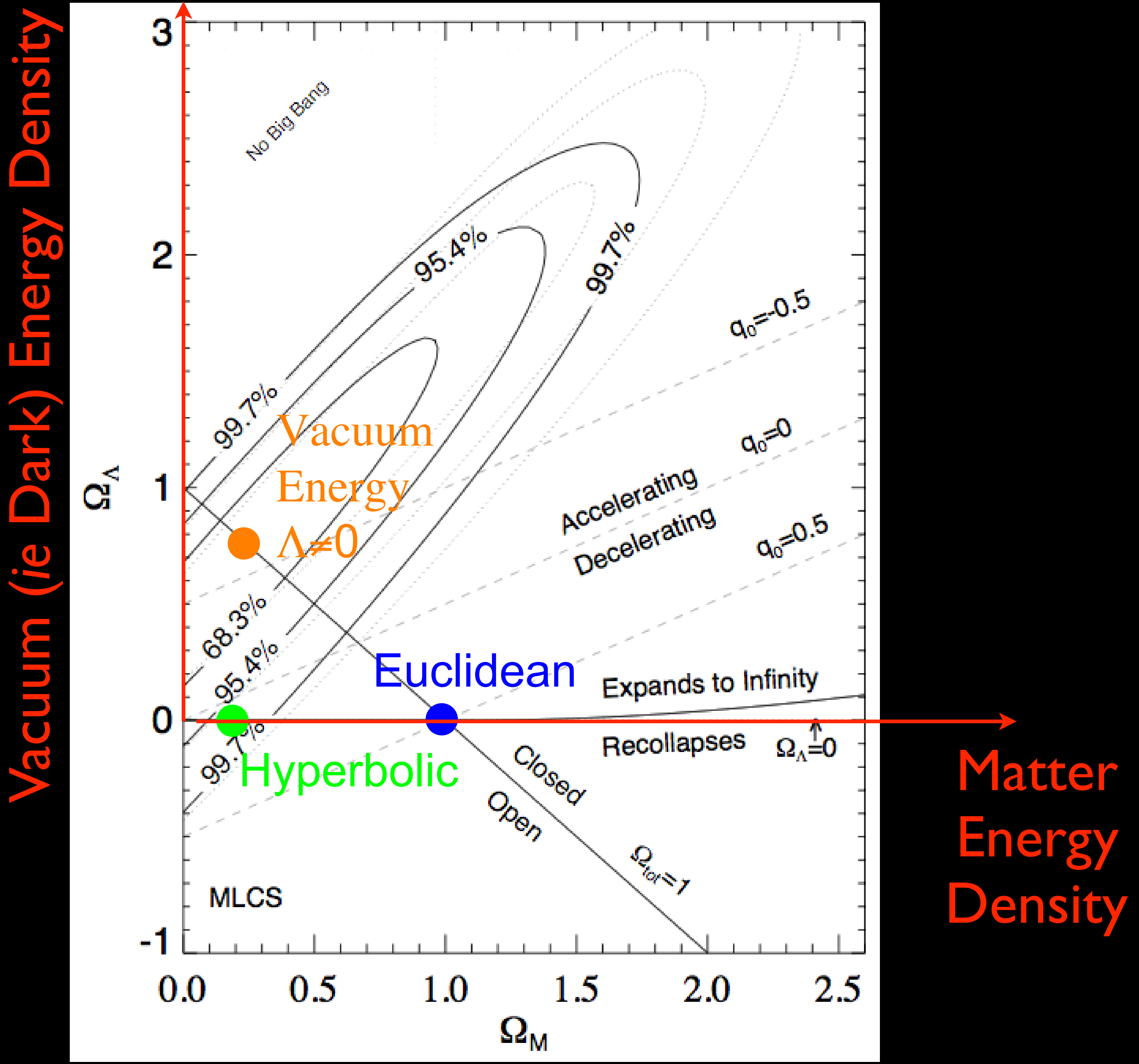
0.5
1.0
1.5
2.0
2.5
Ω_M


Vacuum (ie Dark) Energy Density
Matter Energy Density
Vacuum Energy Λ≠0
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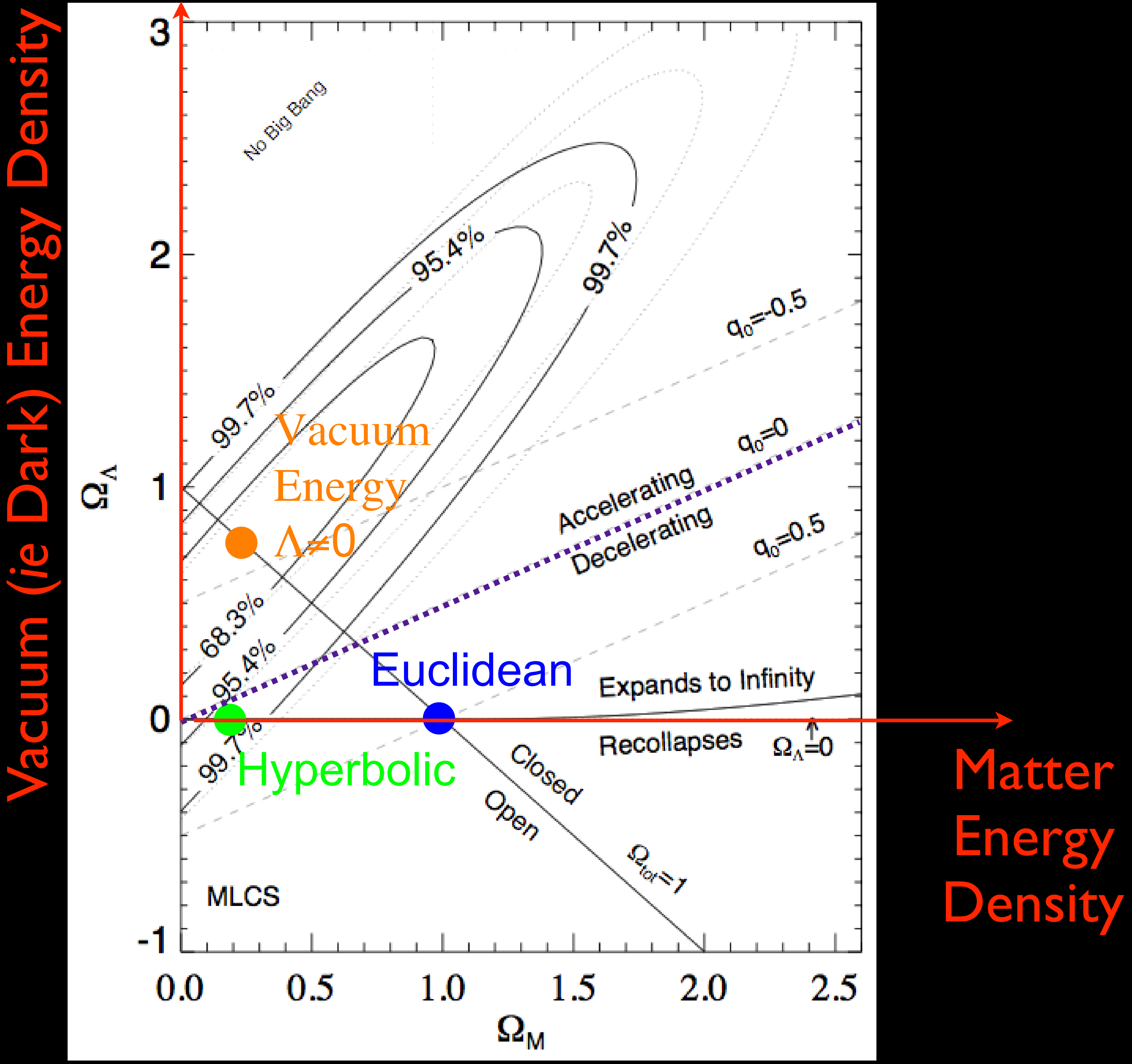
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20th Century	21st Century

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Working Belief	All matter, no dark energy	Geometrically Euclidean

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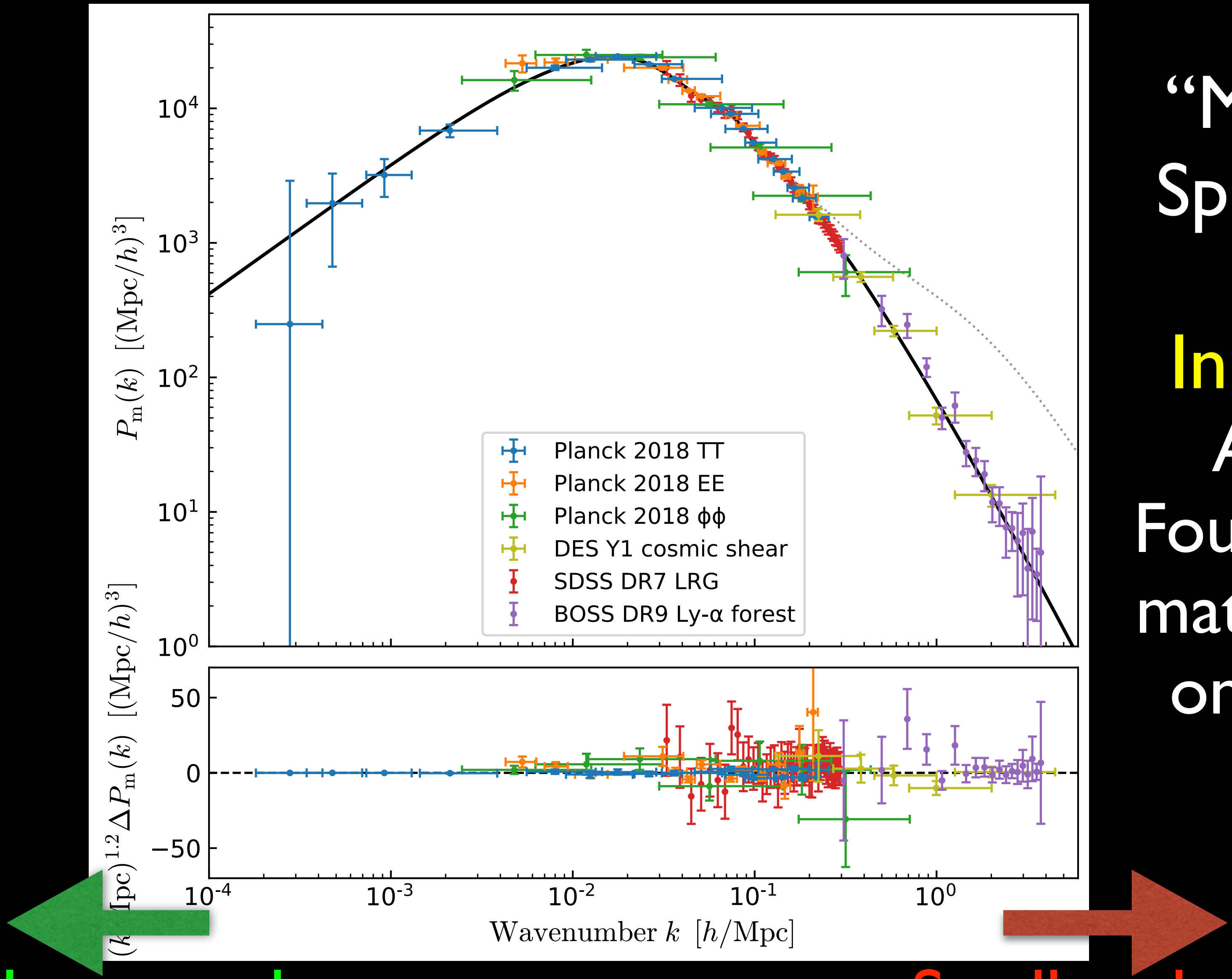
Working Belief	All matter, no dark energy	Geometrically Euclidean
Key Observables	Matter density	Deceleration or acceleration
Unsettling Coincidence	Close to, but not quite, Euclidean	Matter and dark energy densities comparable

Modern Observables

Part 3

$P(k)$: how lumpy is your Universe?



Large scales

Small scales

"Matter Power Spectrum" $P(k)$

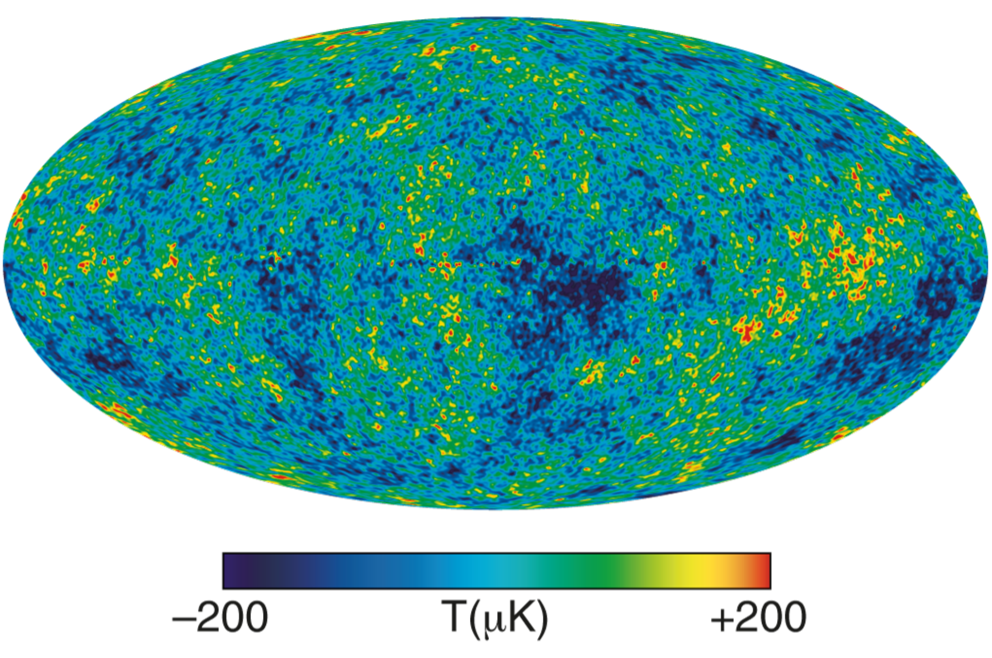
Inhomogeneity:

Amplitude^2 of Fourier moment of matter distribution on spatial scale k

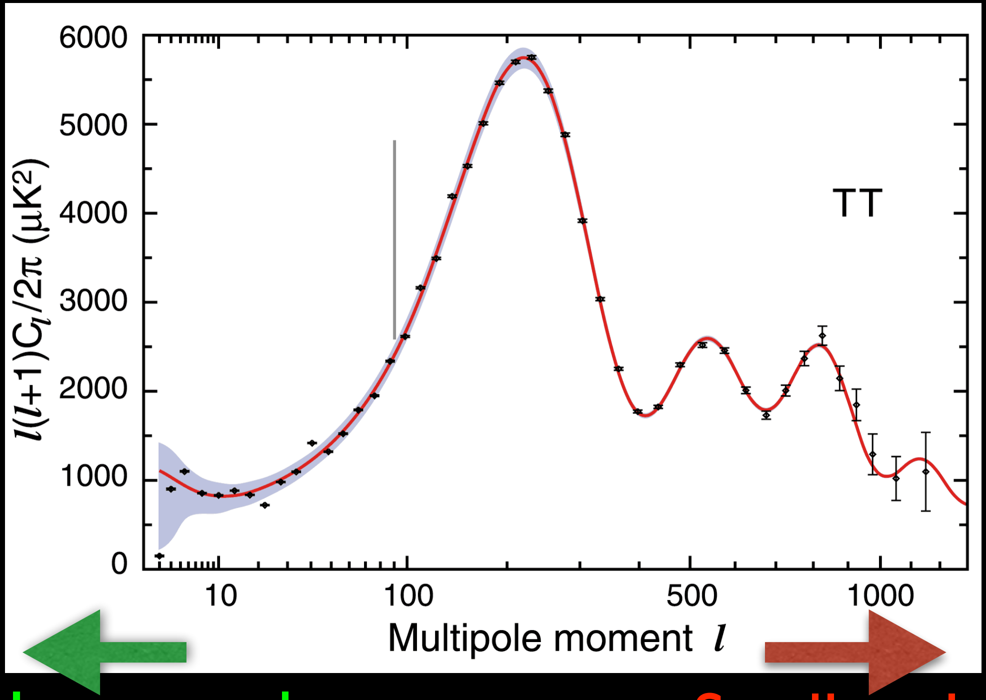
Figure from Chabanier, Millea, Palanque-Delabrouille arXiv:1905.18103

CMB: "Piper at the Gates of Dawn"

All Sky Temperature



Amplitude^2 *vs* angular scale



Large scales

Small scales

Cosmic Microwave Background (CMB) is released when primordial EM plasma de-ionizes at $z \sim 1100$. Temperature pattern reflects matter distribution + sound wave oscillations

Summary

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The uniform, isotropic expanding Universe was first described in the 1920's -- 1930's

During the 20th century, intense focus on matter density and geometry; no exotic energy imagined.

At the turn of the 21st century, distant supernovae show the Universe's expansion to be accelerating, forcing us to entertain exotic "dark/vacuum energy".

Constant dark/vacuum energy will dominate the Universe; but why is the transition happening now? and is the dark/vacuum energy really constant?

What Destiny Awaits

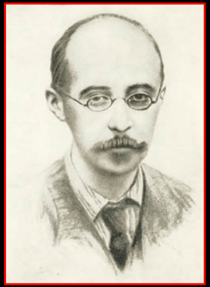
Part 4

$$\left[\frac{\dot{a}(t)}{a(t)}\right]^2 = \frac{8\pi G_{\mathrm{N}}}{3c^2}\,\frac{\rho_0^{\mathrm{Matter}}}{(a(t))^3} - \frac{k^{\mathrm{Curvature}}c^2}{(a(t))^2} + \frac{\Lambda^{\mathrm{DarkEnergy}}}{3}$$

(Another) Friedmann Equation

$$\left[\frac{\dot{a}(t)}{a(t)}\right]^2 = \frac{8\pi G_{\rm N}}{3c^2}\frac{\rho_0^{\rm Matter}}{(a(t))^3} - \frac{k^{\rm Curvature}c^2}{(a(t))^2} + \frac{\Lambda^{\rm DarkEnergy}}{3}$$

(Another) Friedmann Equation



20th Century: Matter vs Curvature

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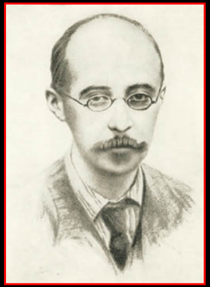

20th Century: Matter vs Curvature

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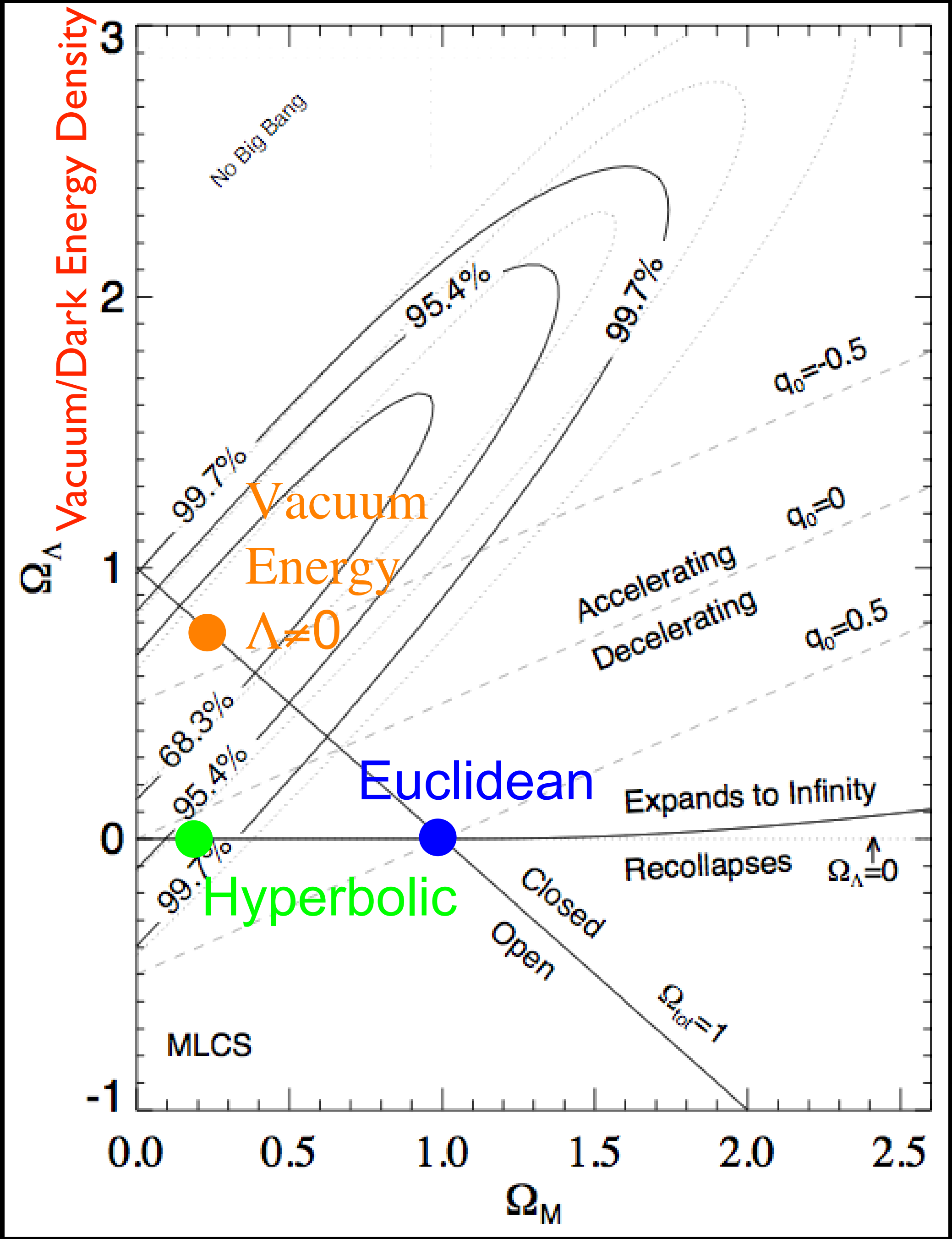
21st Century: Matter vs Dark Energy

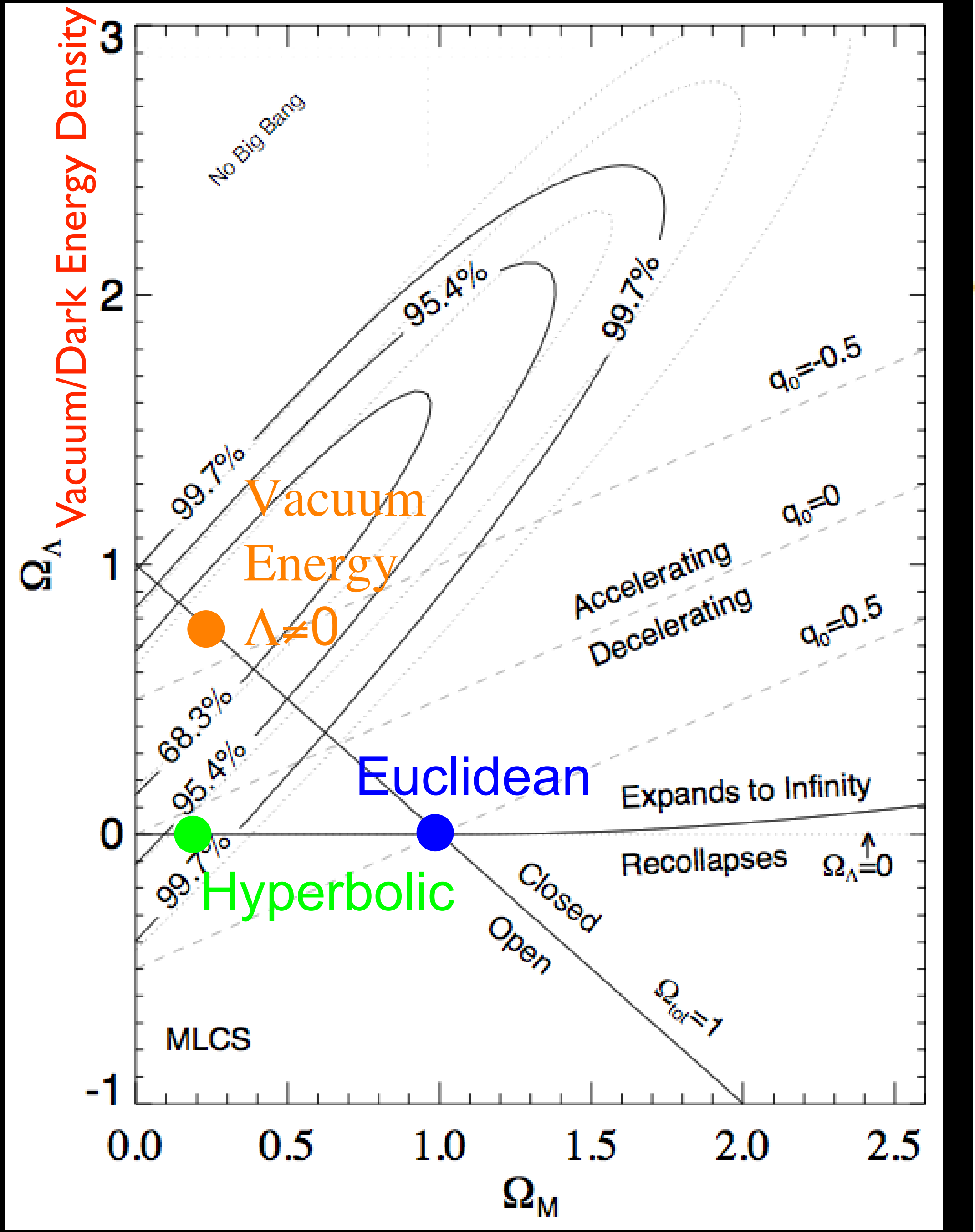
$$\left[\frac{\dot{a}(t)}{a(t)}\right]^2 = \frac{8\pi G_{\mathrm{N}}}{3c^2}\frac{\rho_0^{\mathrm{Matter}}}{(a(t))^3} + \frac{\Lambda^{\mathrm{DarkEnergy}}}{3}$$

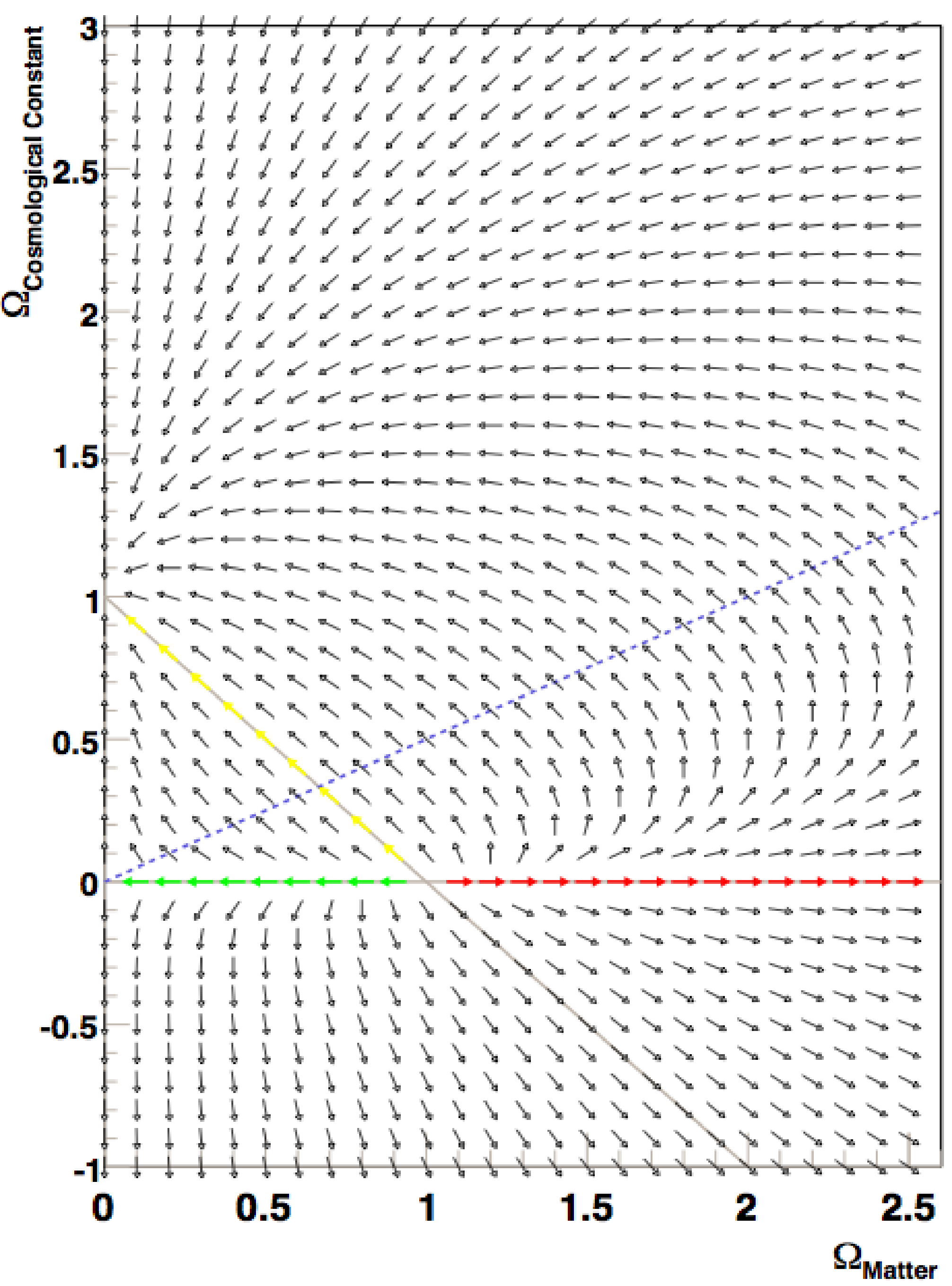
Vacuum/Dark Energy Density

Matter Energy Density

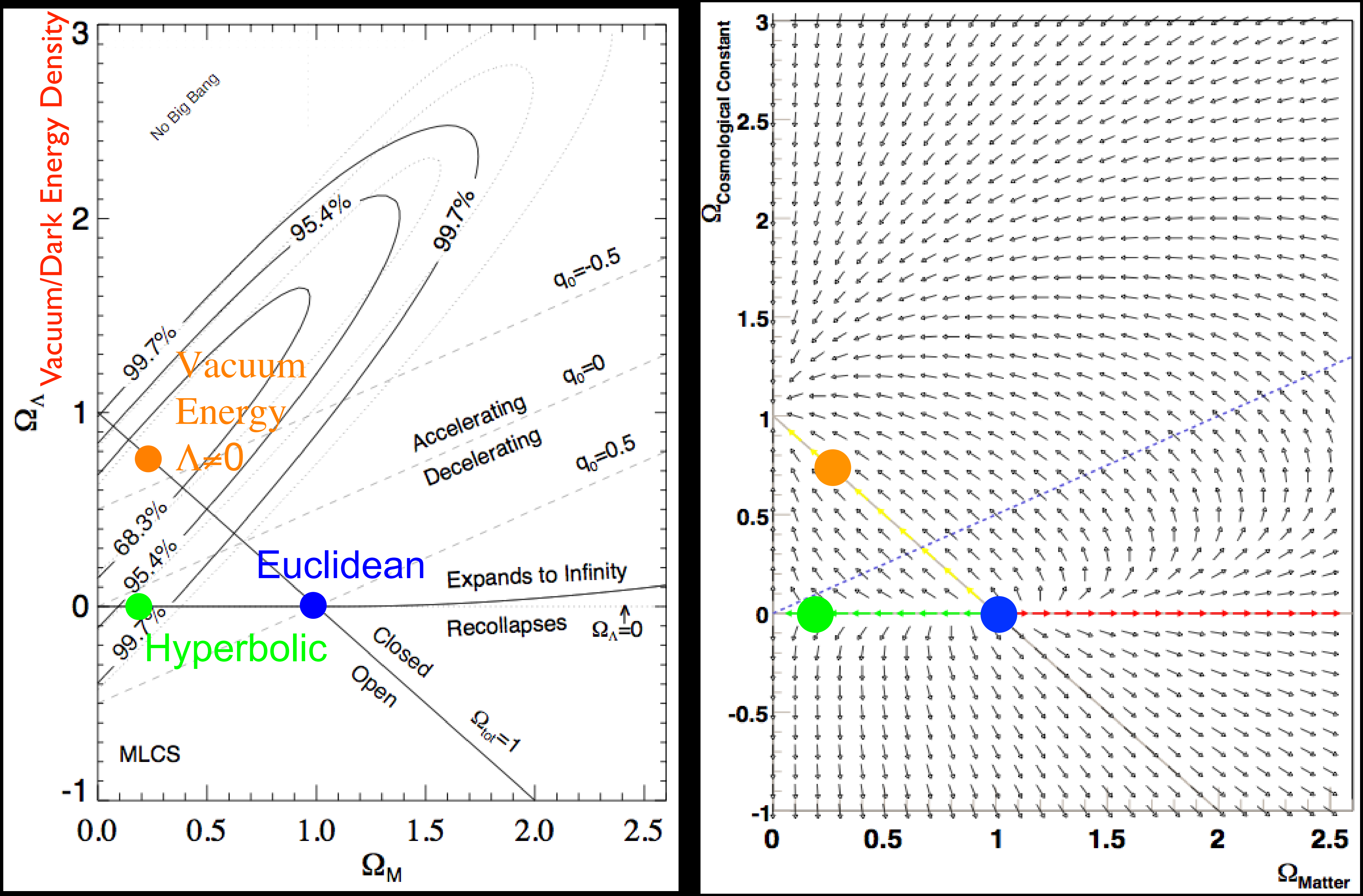


Matter Energy Density





Matter Energy Density



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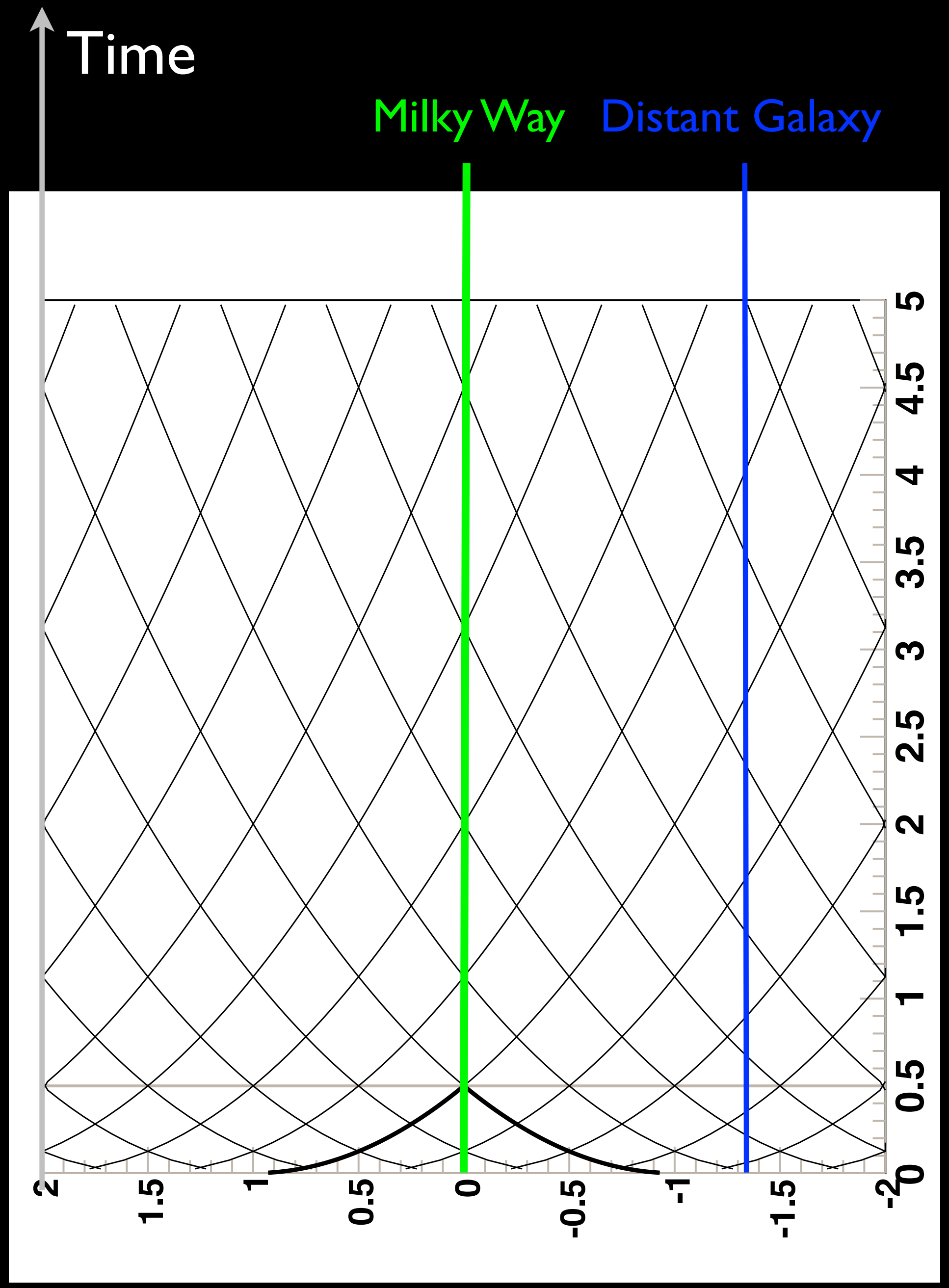
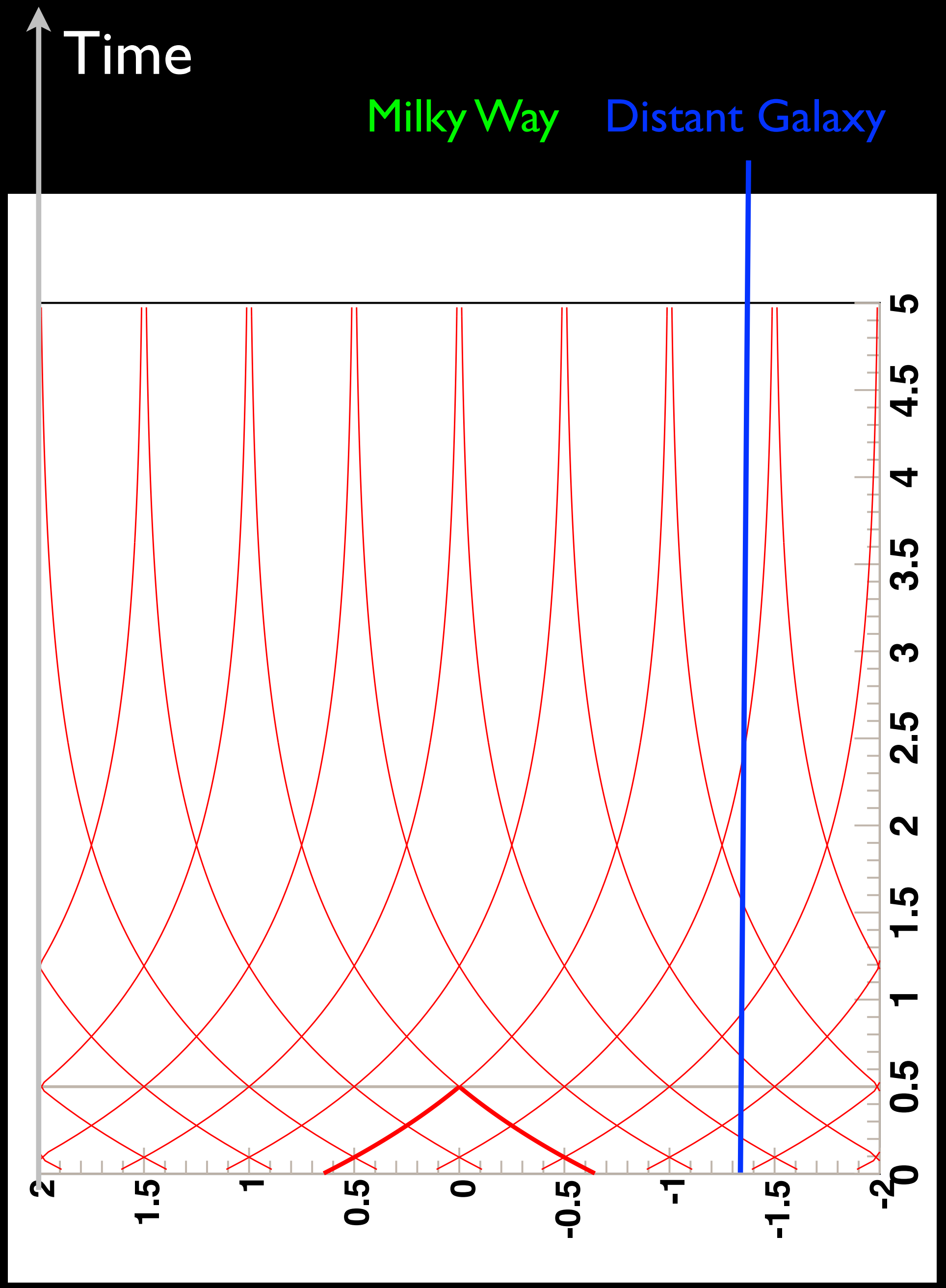


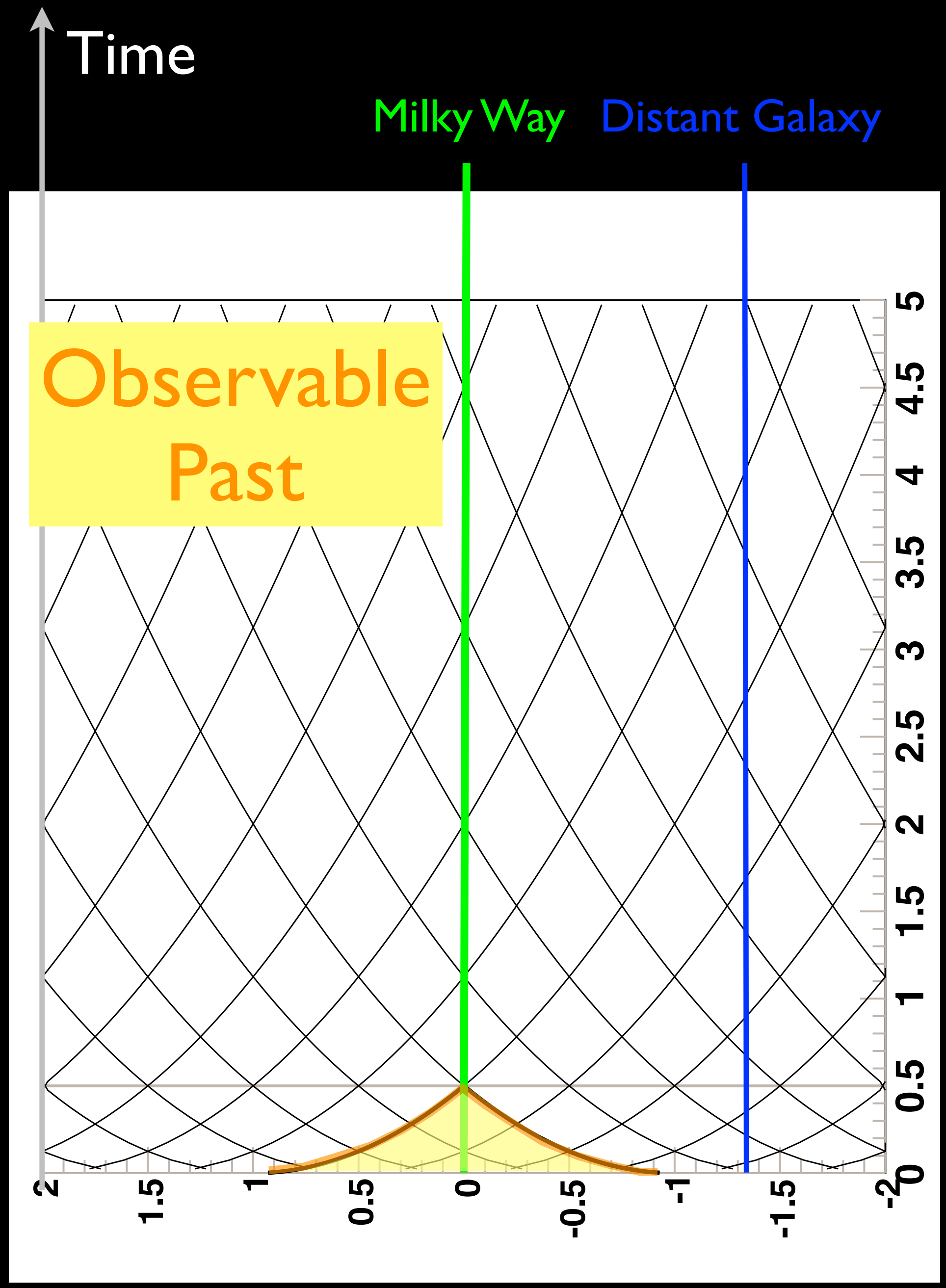
Matter

Now

Big Bang



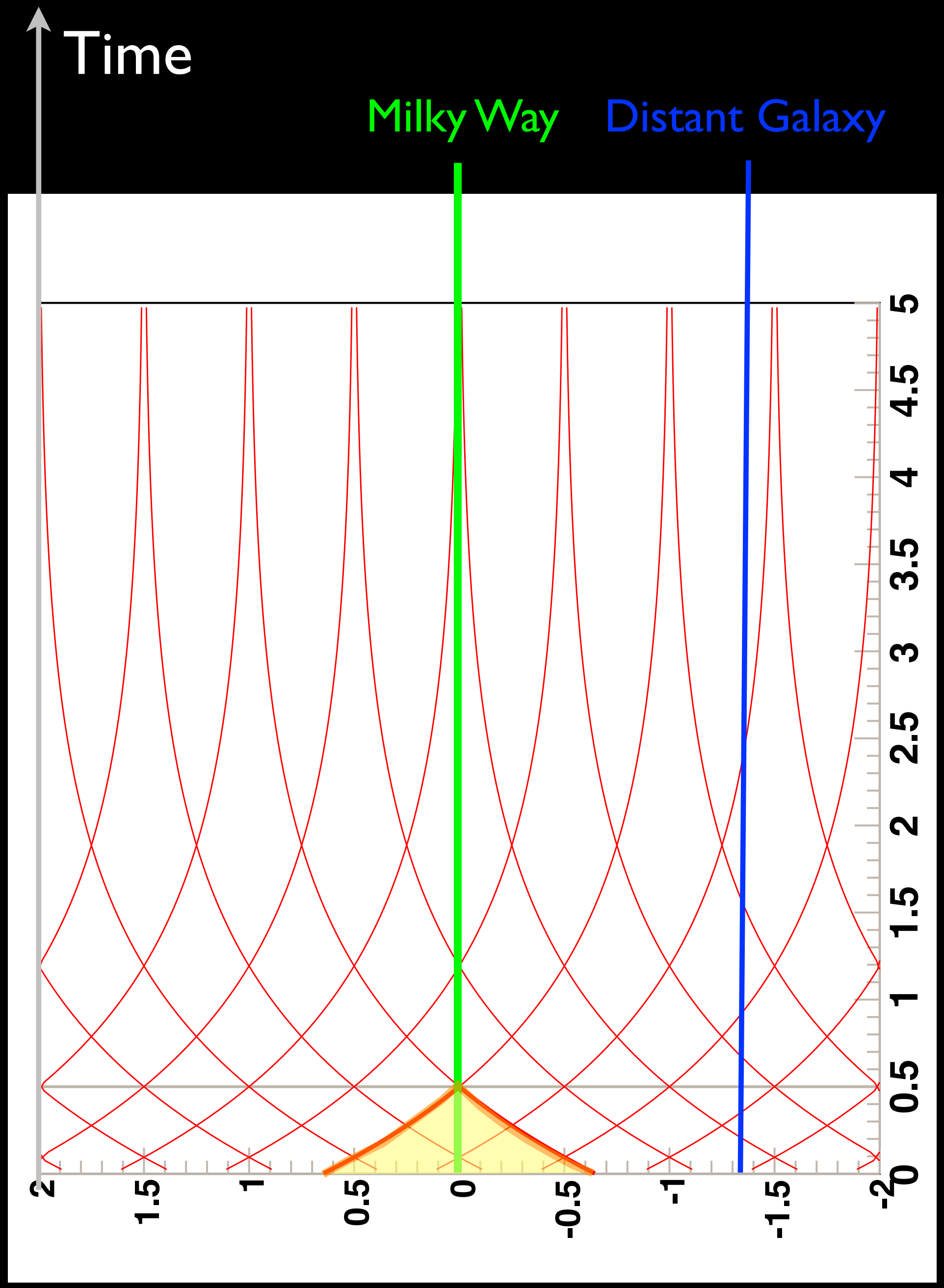
Dark Energy



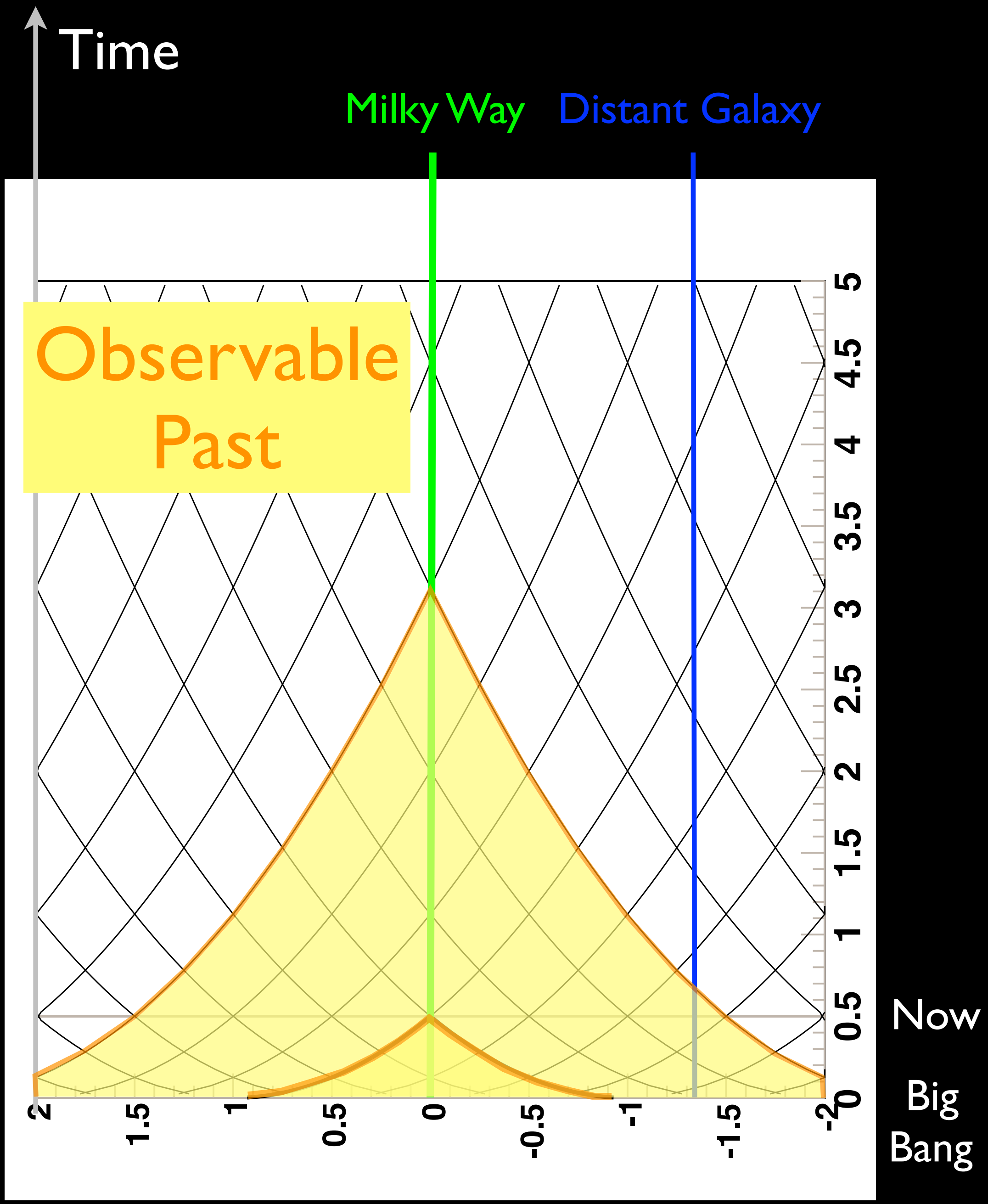
Now

Big Bang

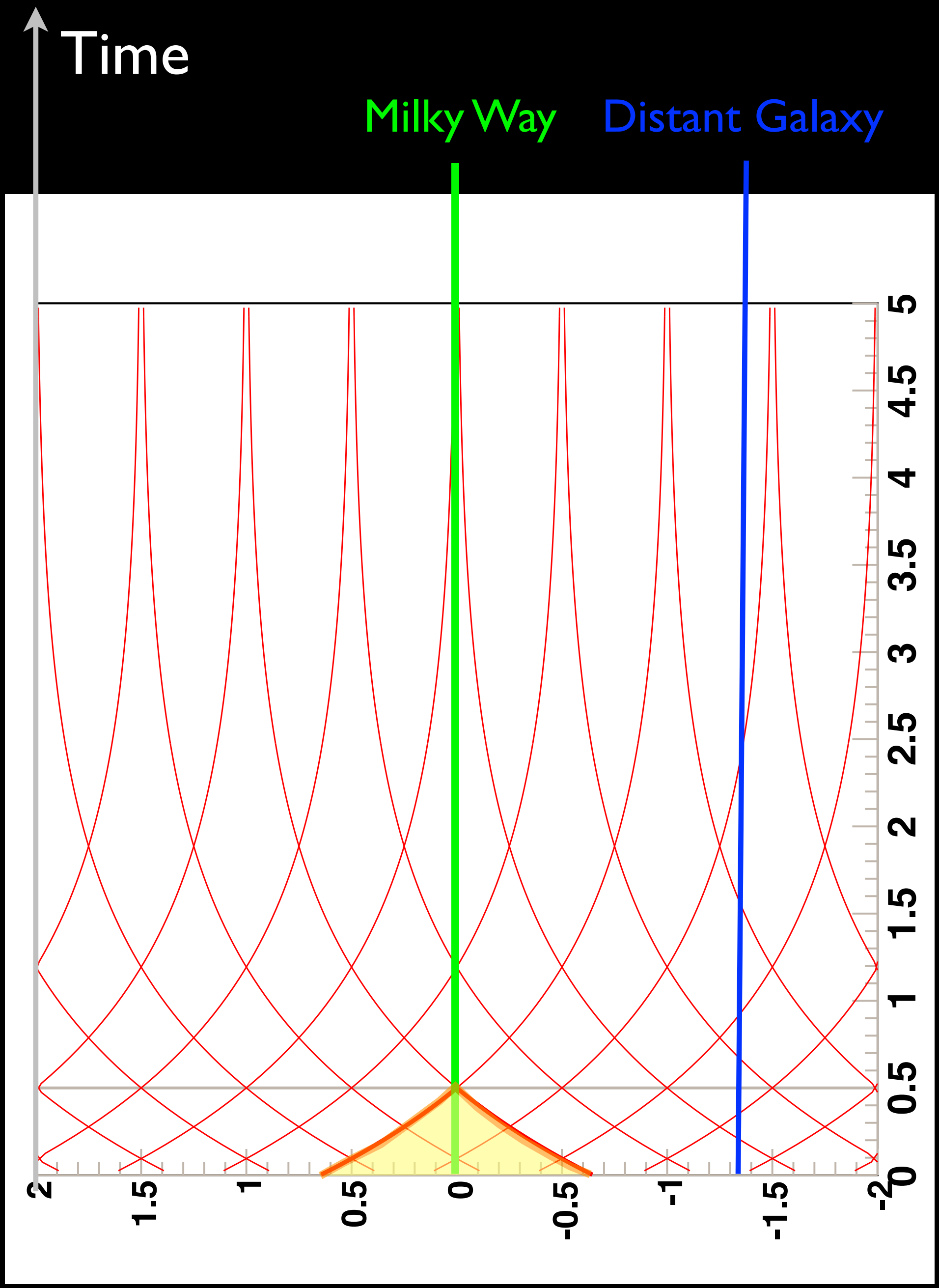
Matter



Dark Energy



Matter



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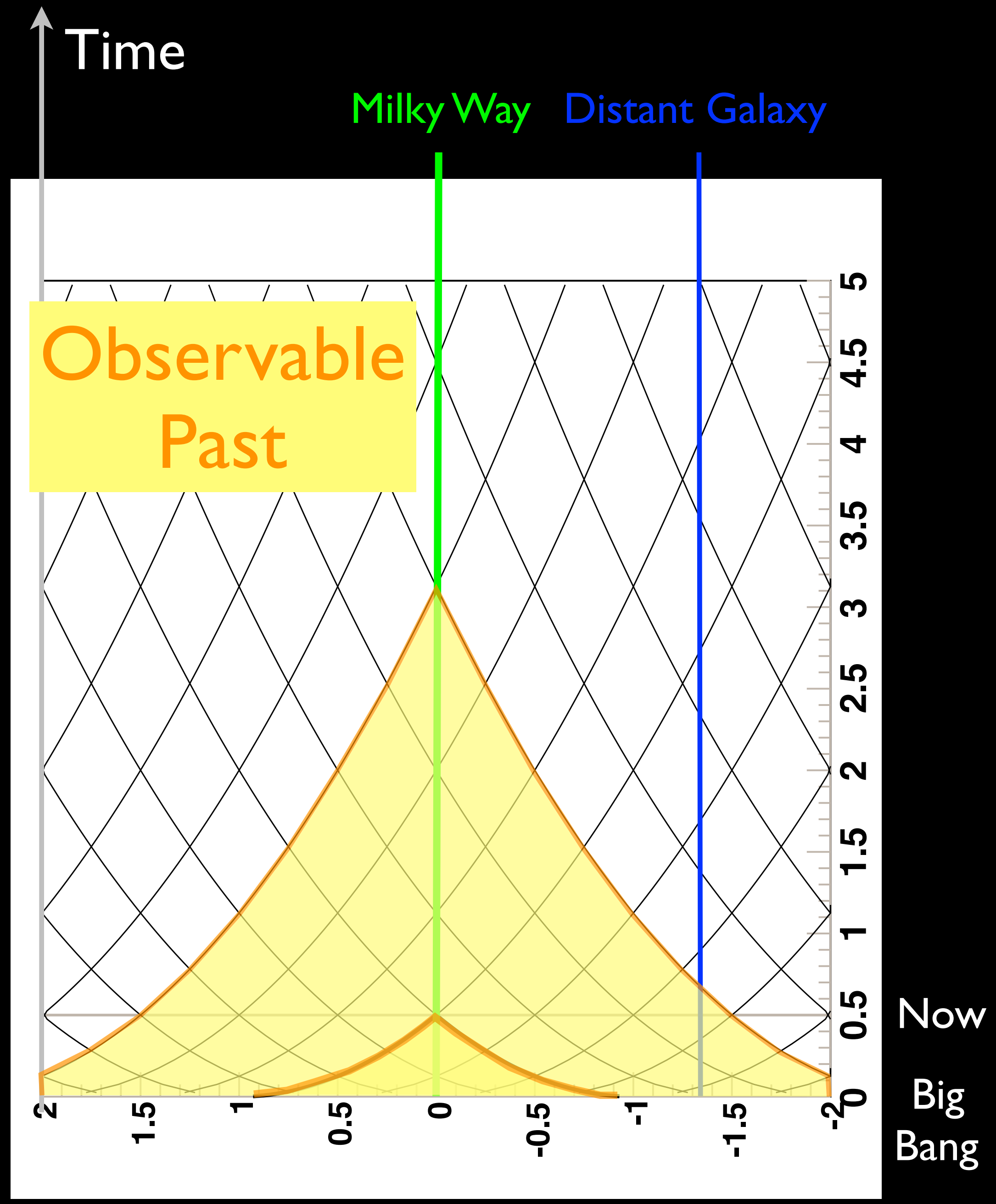

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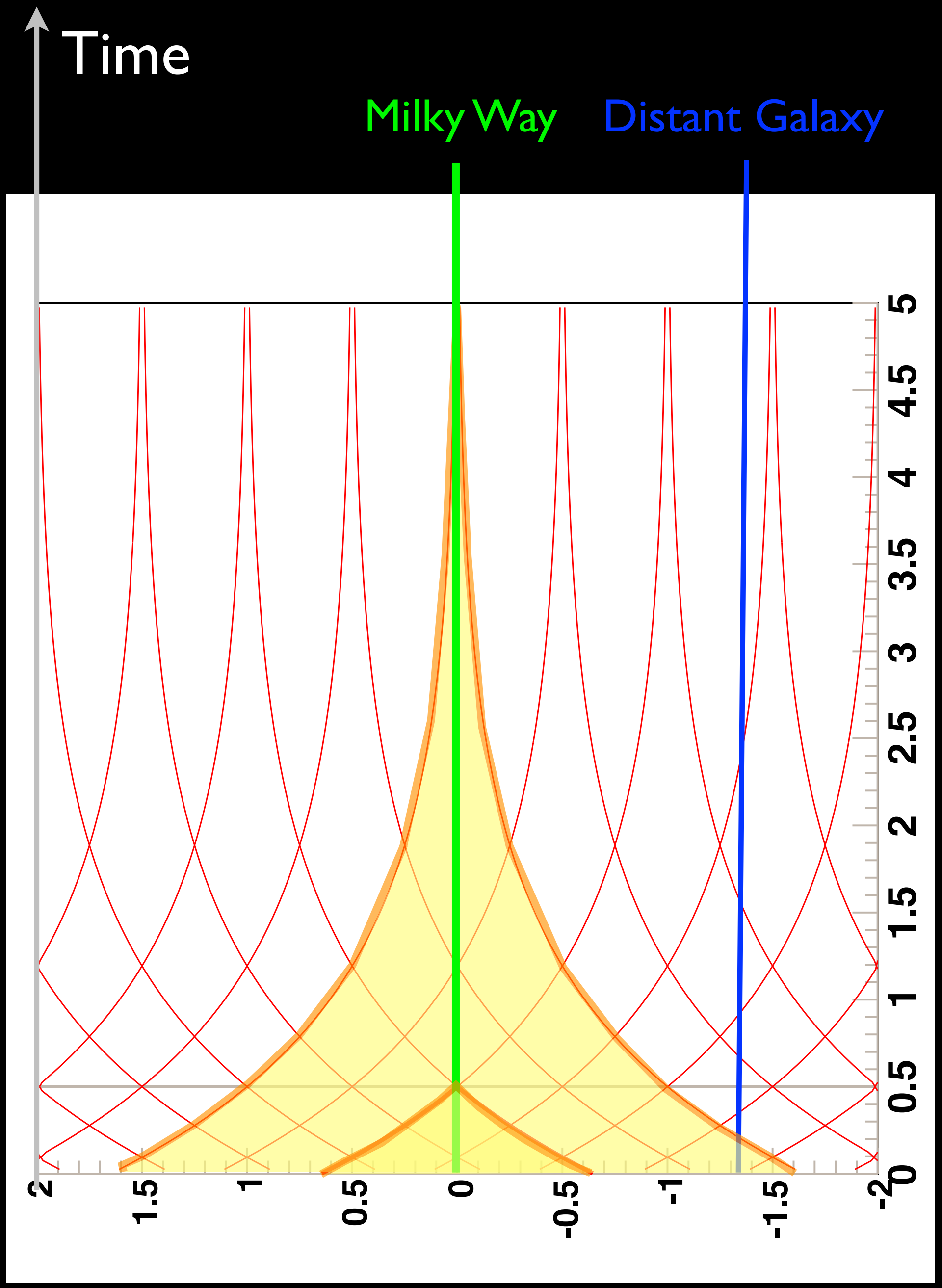

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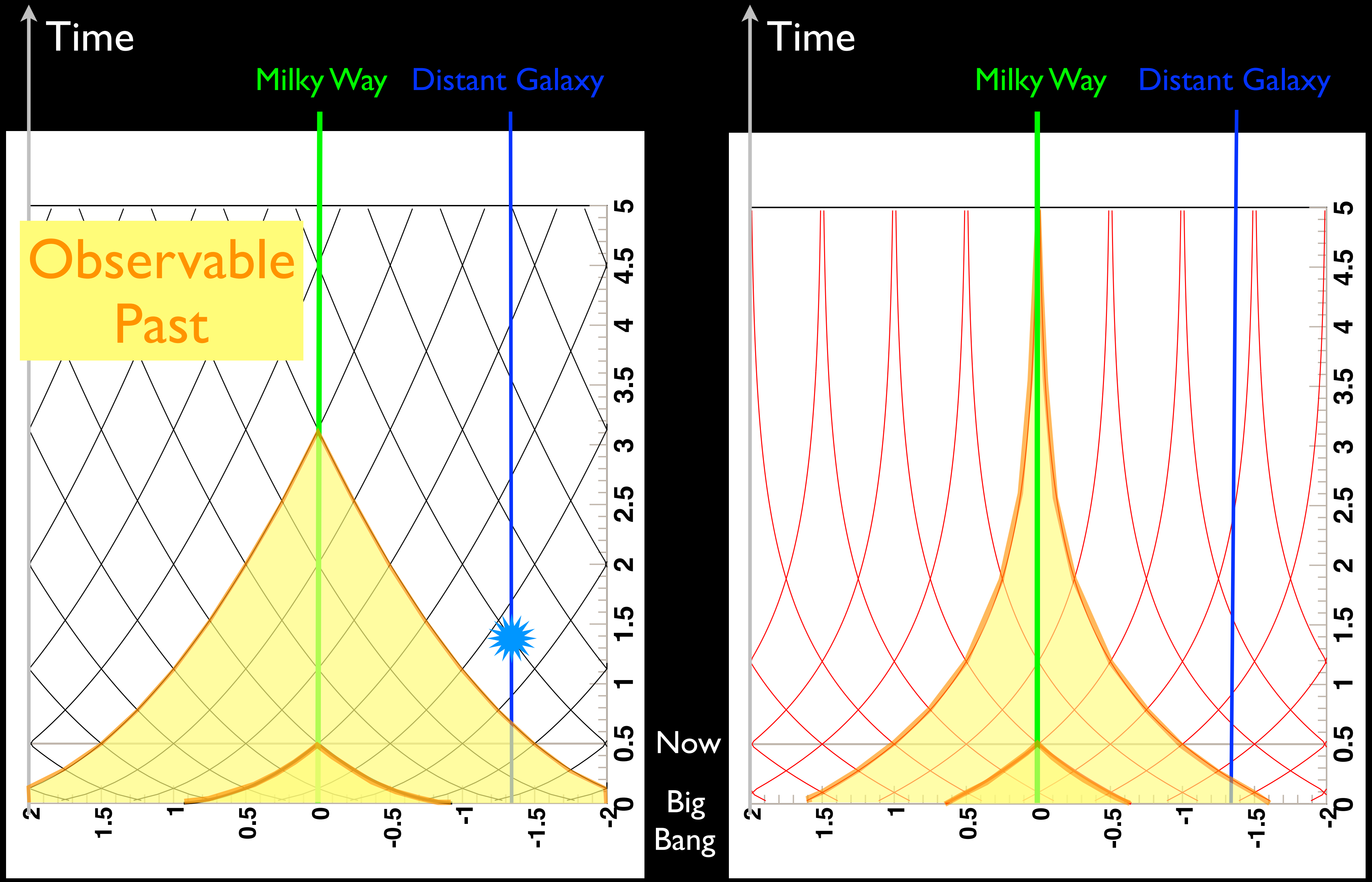

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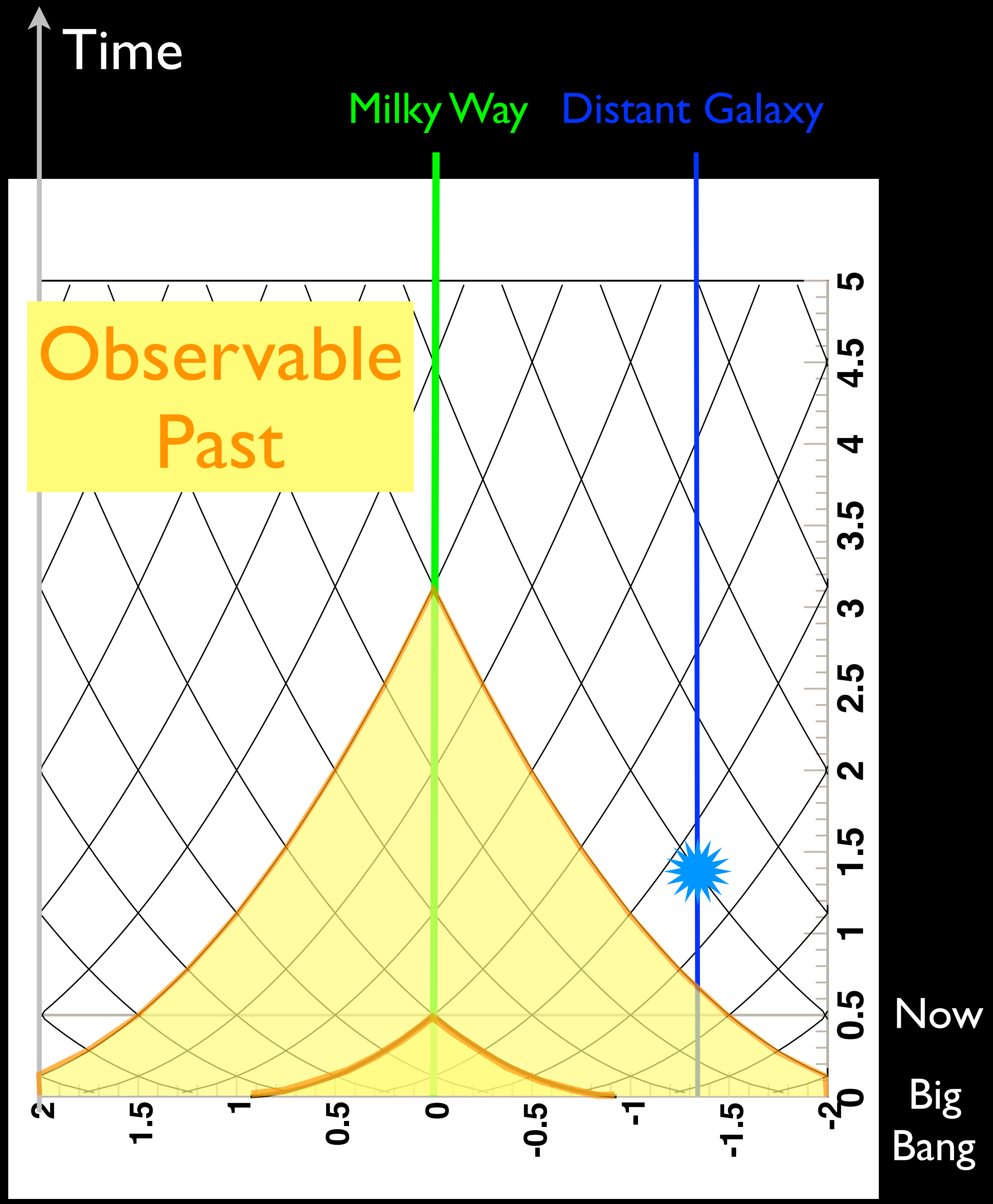

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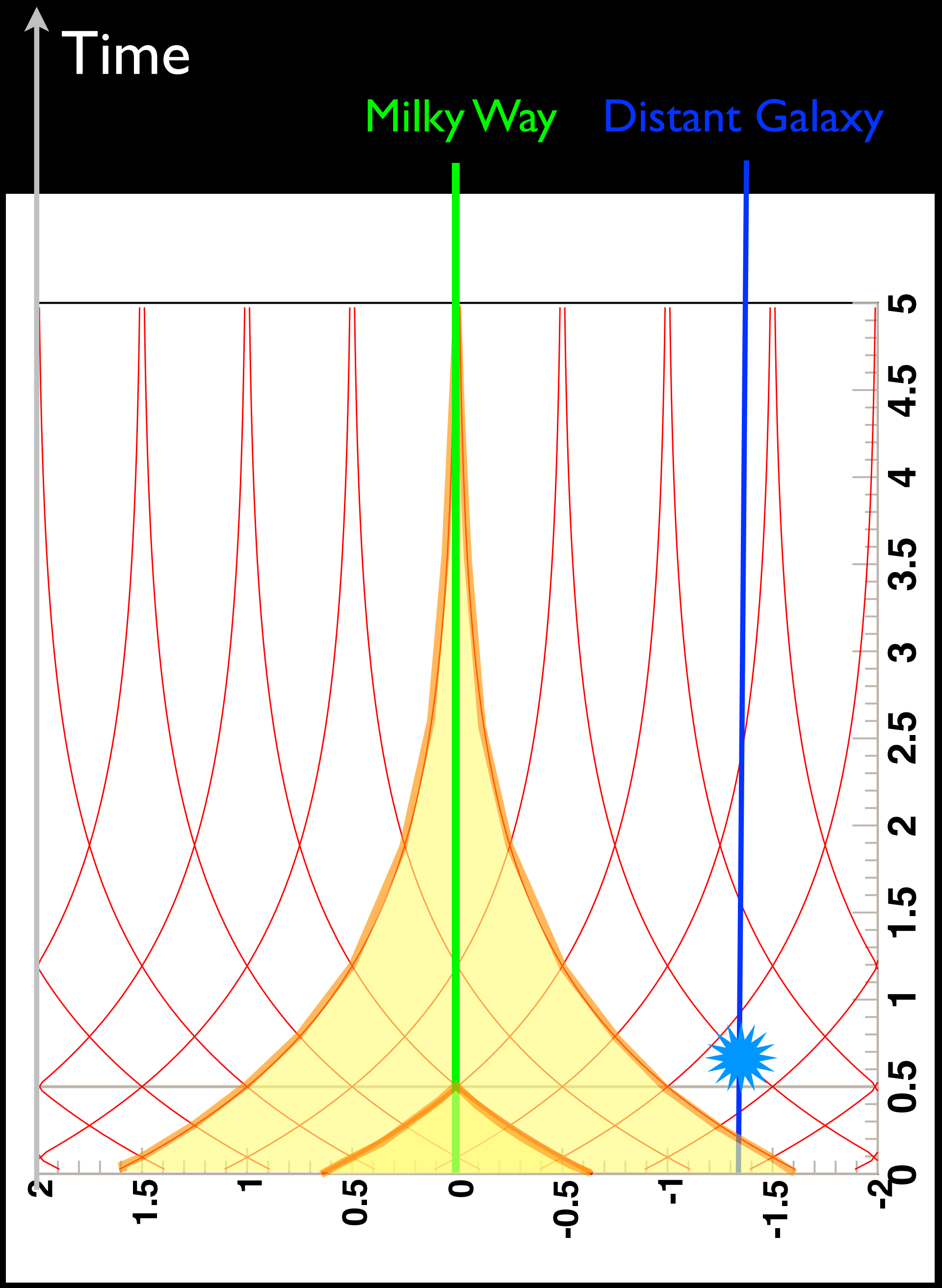

Dark Energy